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Book of Abstracts

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Fleet-Level Effectiveness and Fuel Penalty of Vertical Contrail Avoidance for Long-Range Aircraft in Conceptual Design *Shao-Yu Wang[1], Elif Erden[1], Simon Kirschler[2], Dennis Piontek[2] [1]Bauhaus Luftfahrt, Germany [2]German Aerospace Center (DLR), Germany* 1. Introduction / Objectives Global air traffic volume is expected to grow at an average annual rate of 3.4% through 2050, further increasing the climate impact of commercial aviation. Beyond CO_2 emissions, persistent contrails (PCs) from the interaction of engine exhaust and ambient air contribute considerably to the aviation climate effects. Since PCs only form under specific atmospheric conditions, studies have shown that avoiding flying through persistent contrail regions (PCRs) can reduce PC formation significantly. However, deviating from the design cruise altitude increases fuel consumption for a given mission. This work assesses the fleet-level effectiveness and resulting fuel penalty of contrail avoidance maneuvers via altitude change for long-range aircraft. Furthermore, it evaluates the potential of selected airframe and engine technologies to enhance altitude flexibility. 672

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An Integrated Modeling and Dashboard Framework for Aviation Impact and Transformation Assessment Pascal Bertram, Patrick Ratei, Jonas Jepsen, Prajwal Shiva Prakasha, Björn Nagel *German Aerospace Center (DLR), Germany* 677

System Dynamics and Game-Theory Modelling for Multi-Stakeholder Competitive Analysis in System of Systems Aviation Impact Assessments *H. Szöke-Erös, P. S. Prakasha German Aerospace Center (DLR), Germany 1. Introduction / Objectives* The aviation sector is a hard-to-abate system of systems balancing sustainability and competitiveness across a tightly coupled stakeholder landscape of airlines, Original Equipment Manufacturers (OEMs), airports, and regulators. Despite advances in strategic modelling, a critical gap remains: no existing SoS framework simultaneously captures multi-stakeholder interactions, dynamic market feedbacks, and strategic equilibria under disruption. Limiting existing frameworks application for robust impact assessments and decision-making under uncertainty and competition. This work addresses the research question a) What methodological gaps exist in current aviation impact assessment frameworks with respect to dynamic multi-stakeholder competitive modeling & assessments on a System-of-Systems level, and b) how can SoS dynamic simulation and game-theorey methods be operationalized to close these gaps? To this end, a systematic literature review maps structural limitations in current methodologies, followed by a proof-of-concept competitive model demonstrated in monopoly and duopoly aircraft market setup. 679

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Experimental Aircraft for European Leadership in Aviation (EXAELIA Project)

Chaired by:
Mr. Johan Kos (Netherlands Aerospace Center (NLR), Netherlands)

Experimental Aircraft for European Leadership in Aviation (EXAELIA): Overview of First Results and Initial Roadmaps

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1. Introduction / Objectives

The EXAELIA project addresses the need for more radical changes in long-range aircraft configurations and propulsion concepts with the aim to drastically cut the climate impact of long-range flights and to accelerate the potential entry-into-service of such aircraft to before 2050. To de-risk the development of such radical changes to aircraft and propulsion, novel flying testbeds (FTBs) are introduced. The first objective of EXAELIA is to identify and design concepts of promising aircraft configurations. The next objective is to identify critical aspects of these configurations, including radically new enabling technologies, that need to be de-risked by flight testing. Next, the third objective is to identify the FTBs for carrying out these flight tests. The fourth objective is to predesign the novel FTBs and the flight tests. Finally, the

fifth objective is to prepare the exploitation, including roadmaps for further development of the future long range aircraft (FLRA) concepts and FTBs.

2. Methodology

The project has been organized in two loops. During the first loop, all objectives have been addressed. The following three FLRA concepts have been investigated: a SAF (Sustainable Aviation Fuel) powered Blended Wing Body (BWB), a liquid hydrogen (LH2) powered BWB, and a LH2 powered Tube and Wing (TAW) airplane. Based on top level aircraft requirements , three specific aircraft concepts, together with propulsion concepts and enabling technologies, were designed with advanced multidisciplinary processes, with the objective to minimize their environmental impact. This work also provided insight into criticalities endangering the technical, economic and environmental feasibility of solutions, which need to be de-risked with specific flight tests.

Three different technological areas need a significant breakthrough, which has led to the investigation of the following three families of FTBs: BWB FTB family, LH2-TAW FTB family and Propulsion FTB family. These three FTB families are topically aligned with the aircraft concepts, but are not scaled prototypes of the individual aircraft concepts. Different scales for the FTBs are investigated to address different flight test needs. Additionally, small-scale FTB demonstrators are being built in EXAELIA to investigate criticalities of the FTB families. The concept of FTB "families" relates to the focus on modular design and reconfigurability of FTB components and systems.

To support exploitation, impact assessment methodologies have been developed to assess the impact of such radical long range aircraft, both on aviation and on holistic sustainability. Additionally, roadmaps are developed to illustrate relationships across technologies, test needs, FTBs, and aircraft maturation. For each FLRA concept in EXAELIA, an initial roadmap is created based on the project's technology portfolio by assessing TRLs, reviewing key milestones and challenges, identifying test needs, and incorporating expert input from workshops.

For the initial FTB roadmap, estimates of the development timelines for the first FTB from each family were provided as direct continuation of the design activities in EXAELIA. The follow-on FTBs were planned such that the key learnings from the previous FTB generation can be used to inform their design. This framework provided the basis for establishing the timeframes in which the FTBs are available for testing.

3. Results / Conclusions

EXAELIA contributes to the EASN Conference with presentations covering key results from its first project loop. These include three FLRA aircraft concepts with associated propulsion technologies, three concept definitions for related FTB families, related advancements in technologies and methodologies, also in particular for EXAELIA's FTB demonstrators, and overall impact assessment approaches, alongside initial development roadmaps.

The initial FLRA roadmaps outline the technology developments required to mature the aircraft up to TRL 6 and the tests planned to support this effort, forming the link to the FTBs. This process identifies research gaps and alignment needs for further FLRA developments. The initial FTB roadmap shows the ambitious plan to continue the EXAELIA activities and bring multiple demonstrators to flight.

These results will be further enhanced in the second EXAELIA project loop, with finalized roadmaps paving the way for enabling drastically reduced emissions from future long range flights.

*Acknowledgement:*Funded by the European Union under GA No. 101191922. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Design of a SAF Long Range BWB in the frame of the European Project EXAELIA

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1. Introduction / Objectives

The European project EXAELIA (EXperimental Aircraft for European Leadership In Aviation) has been launched in 2025 in the frame of the Horizon Europe Program with the aim of accelerating the entry into service of a Future Long Range Aircraft (FLRA). The approach is based first on the maturation of key airframe technologies and propulsion systems to be integrated in promising innovative aircraft configuration powered by hydrogen and Sustainable Aviation Fuel (SAF). Second, novel flying testbeds required to derisk the development of these future aircraft are designed and assessed. Last, the project defines roadmaps, but also operational and business plans, for a European flying testbed program. Within the aircraft design activity at conceptual level, 3 FLRA concepts are: a SAF Blended Wing Body (BWB), a Liquid Hydrogen (LH2) BWB and a LH2 Tube And Wing aircraft.
ONERA is the architect of the SAF BWB concept responding to the EXAELIA FLRA Top Level Aircraft Requirements. This paper details the work carried out by ONERA during the first design loop of the project. First, it describes the enrichment of the ONERA BWB Overall Aircraft Design (OAD) process. Then, it presents the SAF FLRA BWB concept obtained at the end of the first design loop.

2. Methodology

As architect of the SAF FLRA BWB concept, ONERA uses its reference BWB OAD process to define a configuration responding to the EXAELIA FLRA Top Level Aircraft Requirements. In the first design loop of EXAELIA, this process has been mainly enriched on the 3 following points, leading to the OAD process illustrated in Figure 1:

- Integration of a propulsion system model for a SAF-powered UHBR engine developed by Technische Universität Braunschweig, providing engine performance data (thrust and specific fuel consumption, SFC) across the aircraft flight envelope (Mach number, altitude), along with mass and geometric characteristics. The paper outlines the modelling methodology and its integration into the aircraft design process.
- Complete revision of the mass model integrated in the Structure Module, which provides the aircraft mass breakdown, and the evolution of both center of gravity position and inertia matrix for several conditions of fuel and payload (passenger and cargo) filling. The mass model uses a mix of equations from mechanics of materials, 1D finite elements and analytical formula. The final paper will detail the Structure Module

and its mass model. The final paper will also present elements about the validation process applied to the mass model, using comparison with reference results.

- Complete revision of the Handling Quality Module, which assesses the aircraft answer to several handling quality criteria. It integrates a Vortex Lattice Method (VLM) module to assess the relevant aircraft characteristics and it uses the aircraft center of gravity evolution provided by the Structure Module. Based on those data, it computes the aircraft center of gravity margin for 3 longitudinal criteria: static margin, approach and take off rotation. The three margins represent then constraints to satisfy in order to define adequate geometries.

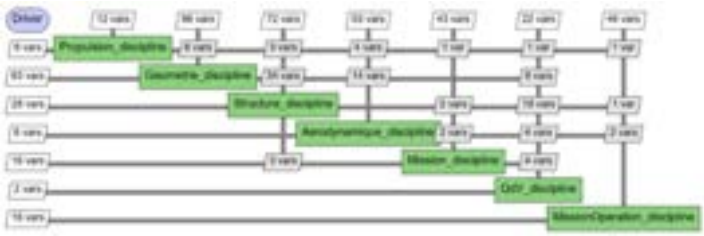


Figure 1. *Diagram of the ONERA BWB OAD process*

3. Results / Conclusions

The first design loop of EXAELIA results in the SAF FLRA BWB configuration illustrated in Figure 2. This configuration is a first baseline that has potential for improvement. Optimization of the configuration is in progress and the final paper will describe the results about the final geometry (airframe and internal layout), performance, mass breakdown and handling qualities.

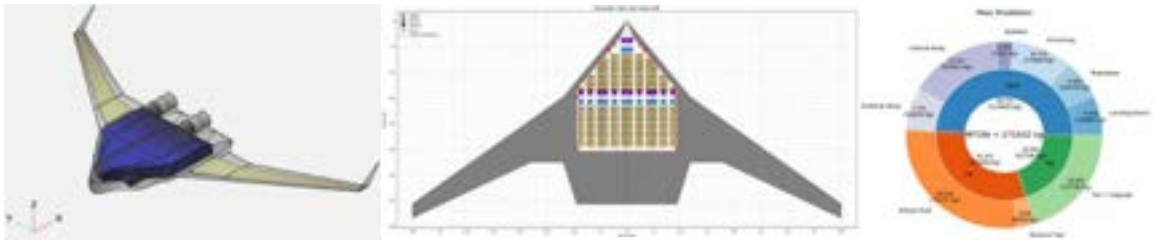


Figure 2. *EXAELIA SAF FLRA BWB configuration (overall 3D geometry on the left showing key components, passenger cabin internal layout in the middle, and mass breakdown using the new Structure module on the right).*

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Conceptual design of a long-range aircraft with liquid-hydrogen propulsion and a truss-braced wing

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1. Introduction / Objectives

To address the need for radical changes in long-range aircraft configurations to reduce climate impact, this paper presents the work on a truss-braced wing (TBW) configuration performed as part of the EXAELIA project's investigation into novel aircraft architectures, targeting entry-into-service in 2050 . The main objectives are: (1) to design and analyze a liquid-hydrogen-fueled truss-braced wing configuration for long-range missions, and (2) to identify critical aspects requiring further de-risking through flight testing. This paper specifically focuses on the first loop of the aircraft design process, presenting preliminary aerodynamic and structural design concepts with integration of liquid hydrogen (LH_2) storage in the fuselage.

2. Methodology

The work presented involves the following aspects of the aircraft design:

- Investigation of various fuselage layout configurations compatible with both the TBW layout and LH_2 storage within the fuselage structure, addressing space constraints. In particular, the advantages and drawbacks of a double-decker cabin are studied and its effect on weight and aerodynamics is investigated, with a focus on maximum utilization of the fuselage volume.
- Assessment of different lift distribution patterns for aerodynamic efficiency optimization. This study will cover the search for a suitable spanwise lift distribution, considering also the load shares between wing and strut for cruise and low-speed, as well as the impact of the selected strut attachment location.
- Integration of high-fidelity results for the mechanical and aerodynamic design of the high-lift system and their impact on the movables layout.
- For the Initial design of the wing planform, the incorporation of a mid-fidelity aero-structural wing structure sizing tool allows to account for aeroelastic effects early in the design process. This enables systematic evaluation of different wing and strut geometrical parameters and lift distributions for the estimation of the structural mass of the wing and the strut.

This initial design loop establishes the foundational concept that will be refined in subsequent loops with increased-fidelity disciplinary assessments. The methodology prioritizes conceptual validation against key performance metrics while maintaining technical and operational feasibility relative to reference configurations.



Figure 1. *General layout of the investigated aircraft configuration*

3. Results / Conclusions

The preliminary analysis identifies several viable truss-braced wing concepts (such as depicted in figure 1) demonstrating potential for significant climate impact reduction in long-range aviation. The findings from Loop 1 include viable fuselage layouts accommodating LH_2 storage while maintaining an efficient usage of the available volume for payload and systems, and a wing planform balancing low- and high-speed aerodynamics requirements with a low structural mass, to achieve an optimum on vehicle level. Critical aspects requiring further investigations, related in particular to the high-aspect ratio wing, have been identified. The selected designs demonstrate their benefits against the reference and baseline aircraft, supporting further investigation in Loop 2.

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Design of liquid hydrogen fuelled blended wing body aircraft for long range missions

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1. Introduction / Objectives

With the Net Zero target in 2050 and sustainable aviation in mind, different novel aircraft configurations and advanced technologies are investigated in the hope to reduce greenhouse gas emissions. A significant amount of research has been conducted over the last decade, where some research is showing promising results. Blended wing body (BWB) configuration and liquid hydrogen (LH_2) fuelled aircraft are two of the main areas of research amount many. A part of the Experimental Aircraft for European Leadership in Aviation (EXAELIA) project is to explore the possibility of new long-range aircraft with novel configurations and advanced technologies. One of the designs is a LH_2 fuelled BWB aircraft, intended to enable entry-into-service of such an aircraft in 2050. The main objective of this

design exploration is first to identify the potential merits and challenges in this new design, then provide research findings to help accelerate and design a flying testbed.

2. Methodology

GENUS, an in-house built design and analysis software is used to conduct simulations and analysis in the design process. GENUS is constructed with a number of design modules, shown in Figure 1. Each of these modules can be defined by the user based on their needs. This gives a high degree of freedom and flexibility which allows users to design aircraft in different configurations, mission requirements, propulsion system and so on. A number of studies have been conducted using GENUS and cover a variety of designs.

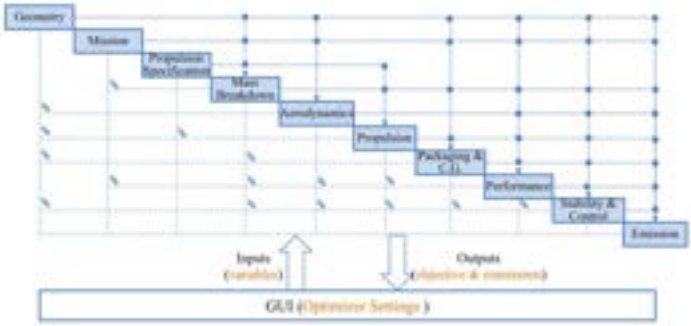


Figure 1. *GENUS framework and workflow*

A top level aircraft requirement (TLAR) is defined based on the A350-1000 with technological level by 2050, which the aircraft is designed to satisfy.

2.1 Geometry and packaging

As a LH_2 fuelled design, one of the main design challenges is the location of the fuel tank. LH_2 has a low volumetric energy density. In another words, a higher fuel tank volume is required despite the fuel weight being lighter compared to traditional kerosene-based fuel. This problem is more significant for a long-range aircraft. At the same time, since LH_2 is a cryogenic fuel, it has to be stored in special designed cryogenic fuel tanks, which are not suitable to put within the wing. With these two new design constraints, a new internal layout for the fuel system and components is
required.

2.2 Performance analysis

The performance of the aircraft is analysed against the TLAR mentioned. The payload range of the aircraft is calculated and analysed. With the limited fuel tank volume, satisfying the required payload range set in the TLAR becomes a challenge.

2.3 Stability and control

One common design challenge for a BWB configuration is the stability and control of the aircraft. In the absence of the tail plane, the longitudinal control of the aircraft is limited and has less authority than traditional tube-and-wind design. The location of the centre of gravity needs to be considered carefully in order to provide an acceptable static margin.

3. Results / Conclusions

A feasible design will be presented in the results and conclusion. This will include a list of

merits of using this design compared to baseline design, A350-1000; a list of design challenges accounted during the design process.
A conclusion of the feasibility of using LH2 fuelled BWB configuration as a future long-range aircraft will be drawn based on the previous results. In addition, what are the features that are needed to be further investigated using flight tests to move forward with the design.

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Modelling and preliminary design of liquid-hydrogen fuel systems for future long-range aircraft

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1. Introduction / Objectives

The aviation industry faces a difficult challenge in achieving carbon neutrality by 2050, requiring a shift from kerosene to more sustainable alternatives. Liquid Hydrogen (LH2) is a promising alternative because of its high gravimetric energy density, yet its introduction requires a fundamental reimagining of aircraft architecture and fuel management systems. In particular, low volumetric energy density compared to kerosene, and cryogenic storage conditions are critical aspects that must be tackled.
The objective of this study, performed within the EXAELIA project, is to present an integrated modelling tool that captures the interdependencies between the general layout of next-generation long-range aircraft and elements of the LH2 fuel system. The subsystems considered in this work are: the LH2 tank, the pipes to deliver LH2 to the engine, the venting lines, the LH2 pumps and the heat exchangers for hydrogen conditioning.
The different components must respect geometrical and thermodynamical constraints that can change depending on the aircraft configuration.

2. Methodology

The methodology adopts a multi-level approach for the preliminary sizing of LH2 storage and distribution system for given mission fuel mass and engine requirements. In the present study, two different hydrogen-powered aircraft configurations are considered: tube and wing (T&W) and Blended Wing Body (BWB). A possible layout for the T&W is displayed in Fig. 1.
Two tank types are considered:

- A double-shell aluminium tank, featuring vacuum and Multi-Layer Insulation (MLI). The thicknesses of internal and external shells are computed according to membrane theory and Roark's formulas .

- A composite tank, sized via finite element method (FEM), also vacuum-insulated with MLI.

The tank design (e.g. number of vessels, layout, shape, insulation) depends on the fuel mass required, the different aircraft configurations, geometrical constraints, operating pressure, and dormancy time.
Aluminium pipes, insulated with MLI, are modelled with the same approach used for the tanks. The pressure losses for both liquid and gaseous phases of hydrogen are also considered. The pump power demand is computed as a function of maximum mass flow, fluid conditions, tank pressure, engine delivery pressure and losses through fuel system; its weight is estimated from existing data of cryogenic pumps.
The heat exchanger (HEX) model, adapted from considers the vaporisation and superheating of H2 by recovering heat from turbine exhaust gases, and assumes utilizing nitrogen as carrier fluid to avoid direct contact between hydrogen pipes and hot exhaust gases or air, eliminating risks of oxygen mixing or freezing. The HEX is optimized for mass minimization following specific requirements on H2 and N2 temperatures, maximum allowable pressure losses and geometrical constraints.

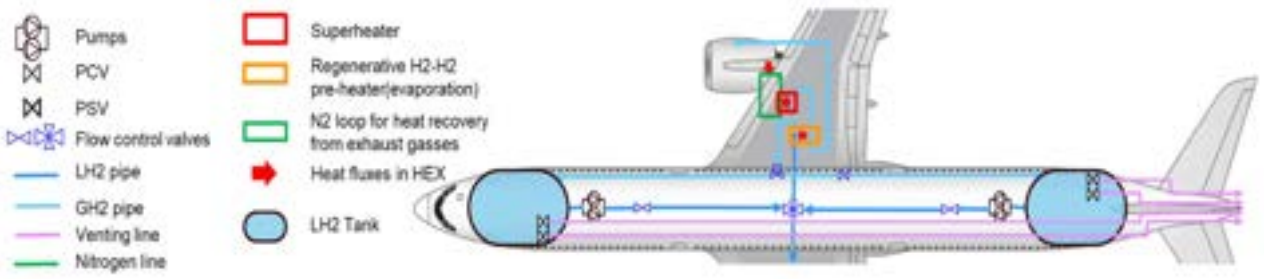


Figure 1. *Example of hydrogen fuel system for T&W configuration.*

3. Results / Conclusions

The tool developed in the EU founded project EXAELIA couples the most relevant subsystems of an LH2 fuel system and identifies the dominant design drivers impacting mass, power requirements, and occupied space for future long-range aircraft. It can also identify strengths and weaknesses of its integration within different future aircraft configurations. This work provides a scalable modeling framework that allows designers to quantify the trade-offs between storage complexity and mission performance with safe and efficient cryogenic propulsion systems in next-generation aircraft. Because of its low computational cost, it is relevant for preliminary sizing and optimization purposes, from single component to entire system level and can be adopted for the earliest design stages.

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Retractable Vortex Generators (RVGs) integration in high lift devices

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1. Introduction / Objectives

One of the objectives of the European project EXAELIA (EXperimental Aircraft for European Leadership In Aviation) launched in the frame of the Horizon Europe Program is to promote and develop new technologies and to increase the effectiveness of the existing ones in order to be implemented on the Future Long Range Aircraft (FLRA). One of the most important features existing on an aircraft is represented by the High Lift (HL) devices, meant to extend the flight envelope by increasing the lift and enhance control at low speeds during takeoff and landing. The paper presents preliminary investigations related to the Morphing Flaps (MF) and Retractable Vortex Generators (RVG) integrated on the wing of a Tube And Wing (TAW) aircraft configuration in terms of structural integration in the wing and their foreseen performances.

2. Methodology

The development of the HL devices is based on a TAW configuration design that contains the definition of the main lifting surfaces basically consisting of planform information (chord lengths, sweep angles etc.), together with a first specification of wing sections thickness distribution along the span, spar positions and a preliminary movables layout. Based on CFD results, the shape for take-off and landing of the MF and the requested position of the RVG was provided. The MF and RVG preliminary internal structures were issued through an extensive review of the open literature, complemented by the expertise and domain knowledge contributed by all project partners involved in the topic. The weight estimation for the high-lift system of TAW configuration aims to quantify the mass impact of the proposed morphing flap architecture, establish a traceable preliminary estimation methodology, and benchmark the solution against a conventional hinged Fowler configuration. The integration impact of the RVG on each flap was assessed based on the existing available space for its own actuators and internal mechanisms requirements, together with a weight estimation methodology.

3. Results / Conclusions

A traceable method for preliminary weight estimation for each HL was provided, showing promising results for the further in-depth investigations. The list of foreseen materials and the assembly technologies that can be used in manufacturing of the HL devices can be the basis of Technological Readiness Level (TRL) maturation. The paper presents the first iteration on the proposed mechanisms that will operate the HL devices.

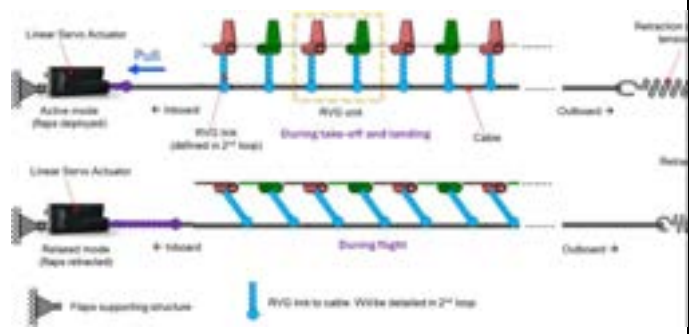


Figure 1. *RVG proposed kinematics*

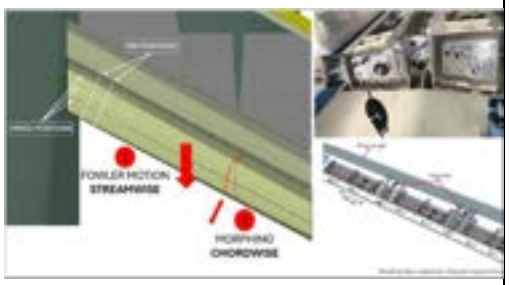


Figure 2. *MF proposed kinematics*

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Development of a Modular Flying Testbed for the Demonstration of Innovative Powertrains

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University of Stuttgart, Germany

1. Introduction

Achieving a substantial reduction in the climate impact of future aviation requires the integration of novel aircraft configurations and disruptive technologies. To accelerate the development and mitigate risks associated with emerging designs and propulsion technologies for future long-range aircraft (LRA), the EU-funded project *EXAELIA* (Experimental Aircraft for European Leadership in Aviation) pursues the development of three families of flying testbeds (FTBs).

One of these FTB-families focusses on the advancement of propulsion and powertrain technologies through experimental in-flight validation of components and integrated powertrain architectures at early development stages, particularly within Technology Readiness Levels (TRL) 4-7. Within these TRLs, a significant gap in maturation capabilities has been identified, as many technologies fail to progress beyond component- or subsystem-level validation due to high cost, integration complexity and certification requirements associated with a flight-relevant testing environment. This study presents a concept for a highly modular FTB particularly tailored to this purpose.

2. Methodology

Prior to concept definition, a comprehensive review of completed, ongoing and discontinued FTB projects is conducted. Furthermore, specific flight test requirements for advanced propulsion and powertrain technologies are identified in collaboration with technology experts. These flight test needs are subsequently translated into preliminary TLARs

for the FTB, forming the basis for the testbed sizing process.
A trade-off study is performed to balance the need for representative flight test data against associated technological and financial risks. Incorporating insights from previous FTB initiatives, a geometrical scaling factor of 20% relative to a state-of-the-art LRA was selected for the FTB. Furthermore, an unmanned platform was selected in order to eliminate crew-related risks and to take advantage from reductions in mass and spatial requirements otherwise allocated to pilot and cockpit systems.
To enable modularity, multiple configurations are evaluated with respect to their suitability for accommodating diverse test cases, including different powertrain components, sub-systems and entirely integrated system architectures. It was decided to integrate a baseline powertrain, independent of the novel architectures and components to the tested, to support the integration and testing of low-TRL technologies. Depending on the maturity and complexity of the technology under investigation, different levels of FTB system complexity can be employed to facilitate progressive validation.
For the development of the Concept of Operations (ConOps), operational requirements of potential test sites are being analyzed, alongside operational practices of previous FTB programs. In parallel, relevant certification requirements are identified based on applicable regulatory frameworks.

3. Results / Conclusions

The study introduces the concept for an unmanned, highly modular FTB, specifically intended for the evaluation of powertrain components and architectures within a TRL range from 4 to 7. The integration of a state-of-the-art baseline powertrain ensures full access to the flight envelope while providing a reliable fallback capability.
The proposed design enables accelerated technology maturation while reducing safety, technical, and financial risks. Its modular architecture allows for efficient integration and flight testing of a wide range of technologies without requiring substantial modifications to the platform. Furthermore, a four-level testing approach supports incremental technology validation, enabling stepwise maturation using a single modular testbed platform.

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Multi-Scale Flying Testbed Strategy for Supporting the Development of Long-Range Liquid Hydrogen Tube-and-Wing Aircraft

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1. Introduction

In recent years, a notable growth in the number of sub-scale flying testbeds (FTBs) has been observed . This trend is driven by the need to accelerate and de-risk novel technology developments for next-generation aircraft through scaled, representative demonstrations as a precursor to full-scale flight testing. Following this logic, the EU-funded project EXAELIA

(Experimental Aircraft for European Leadership in Aviation) identified the development of three modular, multi-scale FTB families as a key enabler for achieving technological breakthroughs with respect to minimizing the climate impact of the next generation of long-range passenger aircraft . One of the three FTB families has the objective to support the development of long-range, liquid hydrogen-fuelled tube-and-wing (TAW) type aircraft through sub-scale flight test vehicles that are complementary to ground-based testing and full-scale flight testing. The present study defines a family of FTB concepts on the basis of relevant flight test topics for this purpose. The concept definition includes a description of top-level aircraft requirements (TLARs), the concept of operations (ConOps) and a feasibility assessment.

2. Methodology

In preparation for the FTB concept definition, current gaps in the European FTB landscape and test needs relevant to scaled-flight testing were identified based on literature study and expert opinions. The findings were consolidated into a long list of flight test needs (FTNs), which subsequently underwent prioritisation according to the following criteria: 1) technology maturity in terms of TRL (technology readiness level), 2) required level of system integration, 3) required FTB operational envelope, 4) flight test instrumentation complexity, and lastly 5) potential positive impact of the considered technology. The prioritisation of the FTNs was conducted independently (N=6) and a consensus was realised through averaging, yielding a quantitative characterisation of the FTNs. Through the application of k-means clustering (k=5) vector quantisation of the FTN consensus, FTNs could be clustered into group topics exhibiting similar FTB characteristics; these more generalised topics were subsequently adopted as targets for the FTB concept generation. Addressing the identified FTN clusters entails that each of the FTB concepts requires modular flight testing capabilities.
The scale of the FTB concepts was determined by correlating testbed scale with the TRL associated with the FTNs within each cluster, thereby enabling the definition of appropriate FTB scales to realise the technology maturation. Concept candidates were developed for each of the clusters based on representative FTNs that were selected due to their proximity to other FTNs within the cluster. Following a qualitative trade-off study, a down-selection of FTB concepts was performed for each FTB scale based on feasibility and potential impact. The selected FTB concepts subsequently underwent iterative development of a ConOps, supported by assessments of both technical and project feasibility. Multiple ConOps assumptions were explored and evaluated in terms of their viability as a capability and service. In this context, the FTB is considered as an enabling capability to facilitate scaled-flight testing, while the ConOps outlines how the FTB services this capability over near- and long-term time scales. These inputs formed the basis for the definition of preliminary TLARs for the selected FTB concepts.

3. Results

The results of this study comprise the conceptualisation of three modular FTB platforms, spanning multiple scales relative to a long-range passenger aircraft (e.g. Airbus A350). These include sub-scale configurations in the 10-15% range for technology demonstration on the experimental proof-of-concept level (TRL 3), 20-30% ranges for further maturation that specifically requires evaluation at high-speed flight conditions, as well as a donor aircraft-based, system-level platform with upwards of 50% scale for relevant aircraft subsystems. Each scale is associated with specific FTNs and corresponding TRL objectives which in combination enable a structured approach to technology maturation from proof of concept via component-level validation to system-level integration at representative flight conditions. The

full paper and presentation will provide an overview of the flight test needs and the technical details of the FTB concepts, including first conceptual design sketches for the smaller scale FTBs. Additionally, the full paper will discuss the development roadmap of the FTBs and outlines their phased introduction into the anticipated development timeline of next-generation long-range aircraft. This ensures that the selected FTBs fulfil the role of de-risking critical technologies from early-stage development up to full-scale implementation.

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Multiscale Modular BWB FTB Design Benefits and Requirements

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1. Introduction / Objectives

The Blended Wing Body (BWB) aircraft design has been around for more than 50 years. With promises such as improving efficiency, range, and emissions, there has been a lot of effort made on designs and flight testing . However, there is no clear guidance on the research benefits of designing and testing different FTB scales.
In 2025, the European project EXAELIA (Experimental Aircraft for European Leadership in Aviation), under the Horizon Europe program, was launched with the aim of developing several flying testbeds (FTB) for future long-range aircraft, including BWB . Testbeds are developed in a way to accommodate the maturation of future technologies and to accelerate the Technology Readiness Level (TRL). The designs will be evaluated on a Dynamic Iron Bird (DIB) to minimize development costs prior to flight testing. This paper explores the effect of various BWB FTB scales and modular designs on TRL maturation for SAF and LH_2 technologies.

2. Methodology

The FTBs development begins with the requirements capture from requested future technologies and the specifics of flight test (FT) needs. These requirements are then developed into Top Level Aircraft Requirements (TLAR) to help constrain the design of the aircraft. The TLARs will then be the basis for the vehicle outer shape design, FTB performance, and internal systems design. That includes the landing gear, actuation and control systems, fuel and propulsion systems, flight test instrumentations (FTI), and other required systems essential for the FTB operation.

Once the TLARs are defined, the FTBs are then split into different scales to be assessed against the feasibility of achieving the mission targets and the benefits of testing each scale towards TRL maturation and knowledge contribution of the BWB design. The assessment mainly focused on the research benefits and the cost analysis at each scale, including the utilisation of Commercial-Off-The-Shelf (COTS) components for the system design, possibility of donor systems (from existing aircraft), and dynamic iron bird concept to reduce costs. The dynamic iron bird (DIB) is essentially the airframe of the FTB without any skins/outer panels installed, which serves as a ground testing platform for TRL maturation and integration before flight testing.
The FTBs then proceed through a standard aircraft development cycle, where preliminary low-fidelity tools (OpenVSP) are used to assess the aerodynamic performance along with rudimentary CAD models for airframe system integration studies. This modular approach increases the flexibility of the FTBs in meeting different test objectives without requiring the development of entirely new platforms. A roadmap was created to illustrate the progression of TRL maturation at each scale of the FTBs (Figure 1).

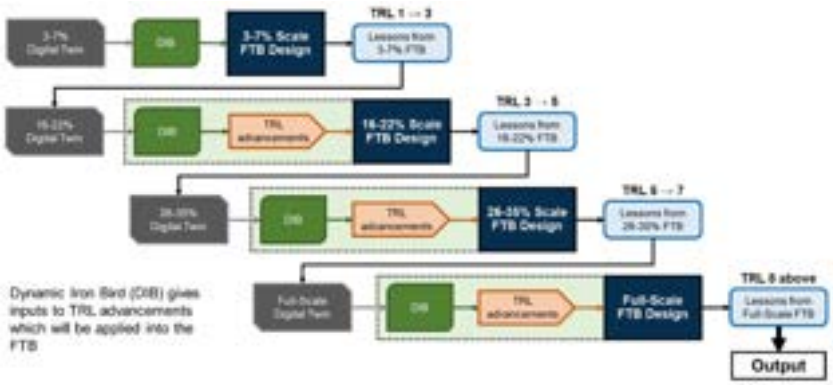
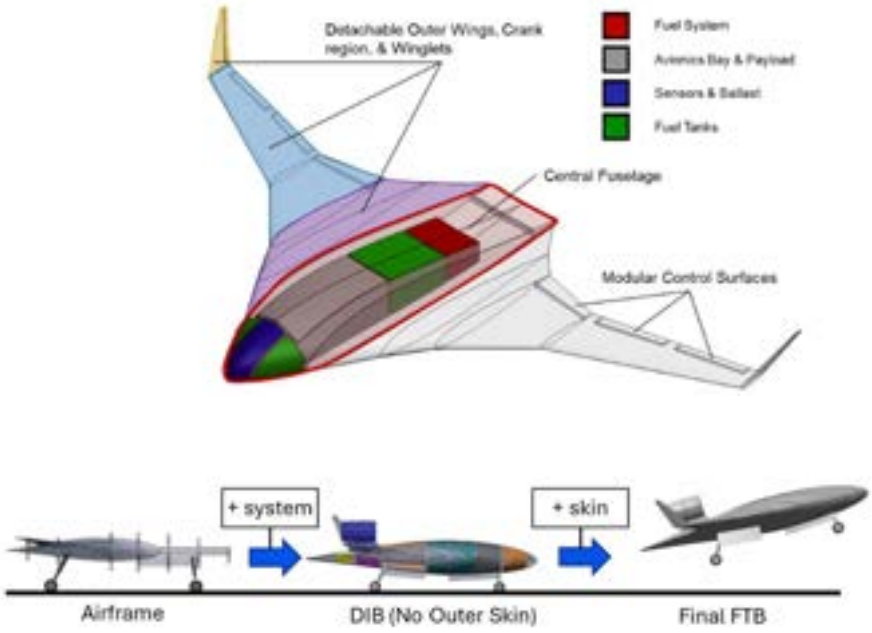


Figure 1. *FTBs TRL Maturation Roadmap*

3. Results / Conclusions

The methodology resulted in the preliminary design of the FTB planform with modular design and the early model for dynamic iron bird (Figure 2), mainly focused on 16-22% scale since it has better operational flexibility to adapt various modular designs, and wider range of economically viable COTS components for the FTB systems. This allows greater adaptability of the FTB to evolving flight test needs and targets, hence future proofing the FTB and reducing long-term costs. The 16-22% scale serves as an intermediate platform between small-scale and full-scale FTBs.



Acknowledgement: Funded by the European Union (Project 101191922 – EXAELIA). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

On-Ground Common Infrastructure and Data Measurement Approach Supporting EXAELIA Flying Testbed Experimentation

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1. Introduction / Objectives

The EXAELIA project aims to develop an experimental flight test programme that encompasses the design and manufacturing of three families of novel scaled Flying Testbed (FTB) aircraft, as well as the assessment of the applicability of innovative measurement technologies and experimental methodologies to these platforms. A fundamental component of this endeavor is the design and implementation of the supporting ground segment.

This paper presents the preliminary test sites identified as suitable for conducting FTBs experimentation and provides a conceptual design of the ground control station and datalink architecture necessary for their operation. The proposed ground segment enables real-time mission monitoring, remote piloting capabilities for unmanned configurations, and the acquisition and storage of relevant experimental data. Furthermore, the paper discusses measurement strategies, instruments, and systems to support noise assessment of scaled aircraft.

2. Methodology

The development of the ground segment begins with the identification of potential test sites suitable for the EXAELIA experimental campaign, followed by the systematic collection of all relevant site-specific information. This process is conducted through an extensive review of the open literature, complemented by the expertise and domain knowledge contributed by all project partners. The conceptual design of the Ground Control Station (GCS) capable of supporting the full range of FTB operations is formulated through a structured definition of system-level requirements. The GCS shall be modular, customizable, and rapidly deployable, while ensuring reliable mission monitoring, remote-piloting capabilities, robust data-management functionalities, and compliance to safety constraints. Additional considerations include configuration management, intellectual-property protection, time-synchronization mechanisms, and interfaces with regulatory authorities. These requirements form the basis for deriving the GCS functional architecture, identifying external actors and their interactions, and defining the associated data-flow structure, collectively covering all operational phases of the planned flight experiments.

The design of the datalink system addresses the need for bidirectional ground-air communication supporting simultaneous telemetry, command and control, and high-rate sensor data streams. The approach is requirements-driven, deriving datalink specifications from the GCS requirements, the advanced sensor complement under assessment, and the FTB operating concepts under development. A traffic classification framework is defined, comprising downlink and uplink traffic classes each assigned Quality of Service (QoS) priorities and latency constraints. A peak load analysis is performed based on the identified sensor complement, including conventional instrumentation, Fiber Optic Sensing, and optical measurement systems, to size the datalink architecture across the three FTB families. To define an aero-acoustic measurement procedure for scaled aircraft several steps need to be taken e.g. the assessment of atmospheric damping methods for higher frequencies, the simulation of FTB noise during operation and the design of an acoustic array for FTBs. The starting point for this assessment is the current noise certification standards for full scale aircraft, i.e. ICAO Annex 16 vol. I, which will be evaluated for scaled aircraft by means of beam forming and (scaled) flight simulations. Furthermore, different atmospheric damping models will be studied for their validity in the higher frequency domain.

3. Results / Conclusions

A preliminary list of potential test sites was identified, providing a comparative assessment of their operational characteristics. The defined GCS architecture is based on a single data acquisition/transmission backbone and four configurable operator stations (figure 1). This configuration ensures mission supervision, data integrity, and operational support. A conceptual datalink architecture was established, which defines a common bidirectional, secure, QoS-enforced ground-air communication framework, with Fiber Optic Sensing identified as the dominant contributor to the downlink bandwidth budget. A three-path data handling strategy was introduced to optimize RF bandwidth utilization. An atmospheric damping correction method suitable up to 1 MHz frequency was selected. Results show that the ICAO reference point shifts to a region of excessive atmospheric damping (figure 2). This can be mitigated by defining a test window with lower humidity/temperature and/or reducing the flyover height. Overall, the conceptual specification of ground infrastructures and measurement approach for FTBs experimentation is nearly completed.



Figure 1. *GCS functional architecture*

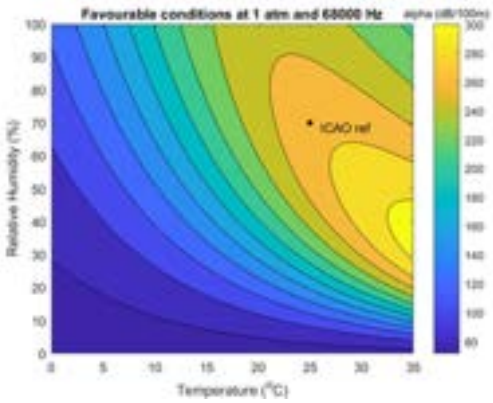


Figure 2. *Atmospheric Damping for 1:8.5 scale A320 for different atmospheric conditions.*

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High fidelity static aeroelastic analysis of aileron spanwise effectiveness in flexible HAR wings

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1. Introduction

Elastic phenomena can be detrimental and sometimes even hazardous, as they reduce control authority and may lead to significant degradation of the aircraft's handling characteristics. The design of modern lightweight wings requires model-based predictive tools capable of resolving the coupled interaction between structural flexibility and three-dimensional aerodynamic effects. Particularly, it is related to flow regimes dominated by viscous, separated, or compressible phenomena, where simplified aerodynamic models fail to capture the underlying physics with sufficient accuracy We address this need by providing a CFD-FEM framework that captures load redistribution, wing twist, and aileron deflection response. The finite-element structural model is augmented with CFD-derived input data to examine the static aeroelastic response under various loads and aileron deflection angles.

2. Methodology

The study provides a high-fidelity static aeroelastic analysis that quantifies the spanwise effectiveness of an aileron integrated into a high-aspect-ratio flexible wing. The

aero-structural coupling is performed using the LoadCast framework, an iterative approach that ensures consistency between aerodynamic loads and structural deformation of a flexible wing. Aerodynamic pressure distributions are precomputed on the undeformed geometry using ANSYS Fluent for a range of angles of attack and stored in a database. During each iteration, LoadCast reconstructs the pressure field on the structural finite-element mesh by accounting for both the global angle of attack and the deformation-induced local angles of attack. The reconstructed pressure loads are mapped onto the structural model, and the resulting deformation is computed using ANSYS Mechanical. This process is repeated until convergence of the pressure field and structural deformation is achieved, providing an efficient aero-structural solution without recomputing flow fields on the deformed geometry at each iteration.
To quantify control effectiveness as a function of spanwise location, the wing is initially equipped with multiple control surfaces distributed along the span. This configuration enables assessment of local control authority and supports identification of spanwise regions particularly sensitive to aeroelastic deformation and control effectiveness degradation. Figure 1 shows the external wing geometry, including the spanwise arrangement of six ailerons and a single flap.

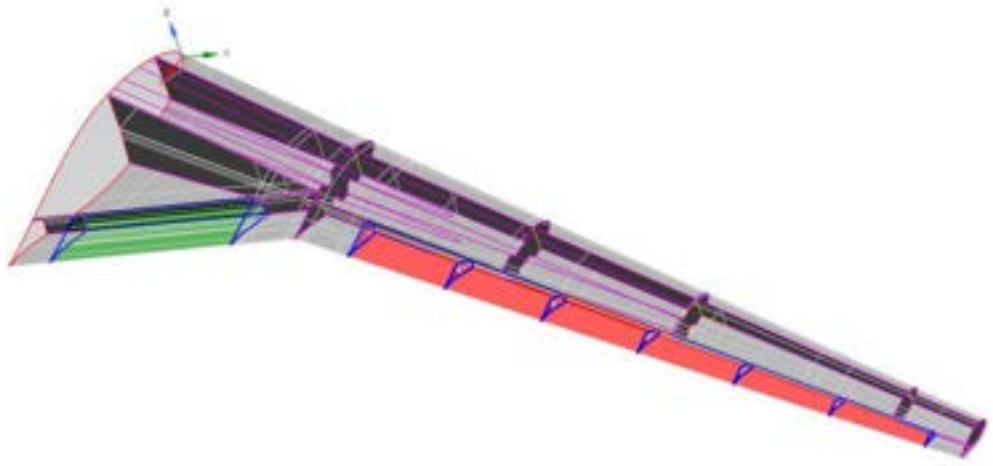


Figure 1. *EXA-16 wing external geometry showing the spanwise division into six ailerons and a single flap.*

3. Conclusions

The results underscore the need to employ high-fidelity aeroelastic simulations during the design of control surfaces. The proposed framework enables more precise estimation of control authority in highly flexible, irregularly shaped geometries and facilitates the optimisation of aileron spanwise location, geometric sizing, and structural stiffness. Future developments will extend this approach to unsteady and dynamic aeroelastic environments, as well as to configurations featuring multiple wing mechanisation elements.

Comparative impact assessment of a future long-range aircraft with an entry-into-service in 2050 – Preliminary Assessment Framework & Results

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1. Introduction / Objectives

Addressing the urgent need for future long-range aircraft (FLRA) that are both climate-friendly and economically competitive, within the EXAELIA project (EXperimental Aircraft for European Leadership in Aviation) , a holistic and comparative impact assessment is foreseen for three disruptive FLRA concepts at aircraft, airport, and air traffic system (ATS) level. These are evaluated against a reference aircraft representing the current state of the art (similar to Airbus A350-1000) and a baseline aircraft incorporating evolutionary technological improvements projected to 2050, with results to be presented in an interactive dashboard to support decision-making and roadmap developments. The assessment integrates models developed by several European research institutes and universities. This work presents the methodology for performing the assessments and integrating these models into a collaborative assessment framework, along with preliminary results comparing the baseline and reference aircraft and including climate impact assessments performed with the Impact Monitor 2 project.

2. Methodology

The impact assessment framework is structured around three use cases. These include: (i) a comparative assessment of new technologies and aircraft concepts at aircraft level, (ii) a noise assessment at airport level, and (iii) an analysis at ATS level of the integration and operation of the FLRA concepts within a future fleet. To implement these use cases, several key steps are required. Based on an analysis within the project of current long-range aircraft operations and future trends—primarily informed by scenarios from the Horizon Europe project PULSAR and data from the DESTINATION 2050 roadmap —requirements and assessment metrics are provided as a key input for the selection of assessment models and scenario definitions. Building on this foundation, the identification of assessment drivers and data requirements is carried out in parallel with the definition of assessment goals and limitations. The process then continues with the analysis of aircraft data generated within the project and the identification of potential data gaps. To address these gaps, data inventories and assumptions are developed through a combination of literature research, stakeholder questionnaires and expert input. Subsequently, dedicated workflows are developed for each use case, integrating the required tools and data streams into a coherent assessment framework. These workflows are executed to generate the assessment results, which are then fed into an interactive dashboard for effective visualization, analysis, and communication. For collaborative engineering, tools such as MDAx for workflow

architecting and CPACS for exchanging information between tools and the dashboard will be used.

3. Results / Conclusions

In alignment with the two design loops defined within the project, the assessment is conducted in two iterative cycles. This work documents the first cycle and the establishment of the assessment framework, identification of data gaps, and testing the methodology. As part of this phase, an initial comparison between the reference and baseline aircraft is performed, alongside the development of a first dashboard mockup. The assessments results will comprise insights distributed along the three use cases on noise, life cycle assessment, life cycle costs, circularity and sustainability performance, climate and social impact and an analysis of future education and workforce requirements. In addition to the assessments, the results will include an exploration of the broader applications of EXAELIA's innovations in aircraft and propulsion by using sensitivity studies on the designs of the FLRA concepts, followed by simplified fuel, environmental, climate and sustainability assessments.

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A Holistic Sustainability Assessment Framework for Aircraft Conceptual Design

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1. Introduction / Objectives

Sustainability considerations are increasingly shaping the development of next-generation aircraft, requiring design
methodologies that integrate diverse aspects beyond environmental concerns from the earliest design decisions . In this context, sustainability must be addressed as a multi-dimensional concept extending beyond environmental performance to include economic viability, circularity, and social impact . Within the framework of the EXAELIA project , a holistic sustainability assessment framework is being developed to support informed decision-making during aircraft conceptual design, where design flexibility is high but data availability is often limited.

2. Methodology

The proposed framework is based on the definition of sustainability as the balanced performance of five key pillars: aircraft performance, environmental impact, cost, circularity, and social impact[1, 2]. Sustainability requirements are derived from a structured stakeholder needs analysis and translated into measurable criteria and sub-criteria. Environmental impacts are assessed using Life Cycle Assessment (LCA) methodologies, while economic performance is evaluated through Life Cycle Costing (LCC). Circularity and social indicators are incorporated alongside traditional technical and financial metrics, enabling a comprehensive evaluation of alternative aircraft configurations.
To operationalize the methodology, a dedicated computational tool to support decision

making has been developed, enabling the integration of conceptual design datasets and the definition of criteria weights (Figure 1). Multi-criteria decision-making (MCDM) techniques, including Weighted Sum, TOPSIS, and modified TOPSIS approaches, are implemented to support sustainability-driven ranking of design alternatives. Sensitivity and uncertainty analyses are also included to evaluate the robustness of results and address the inherent variability associated with limited conceptual design data.

3. Results / Conclusions

The proposed framework enables the comparative ranking of alternative aircraft configurations through the calculation of a Sustainability Index (SI), supporting systematic trade-off analysis among sustainability pillars. By embedding sustainability assessment within the aircraft conceptual design phase, the methodology supports transparent and data-informed decision-making and contributes to the development of more sustainable aircraft concepts aligned with future aviation requirements and the objectives of the EXAELIA project.

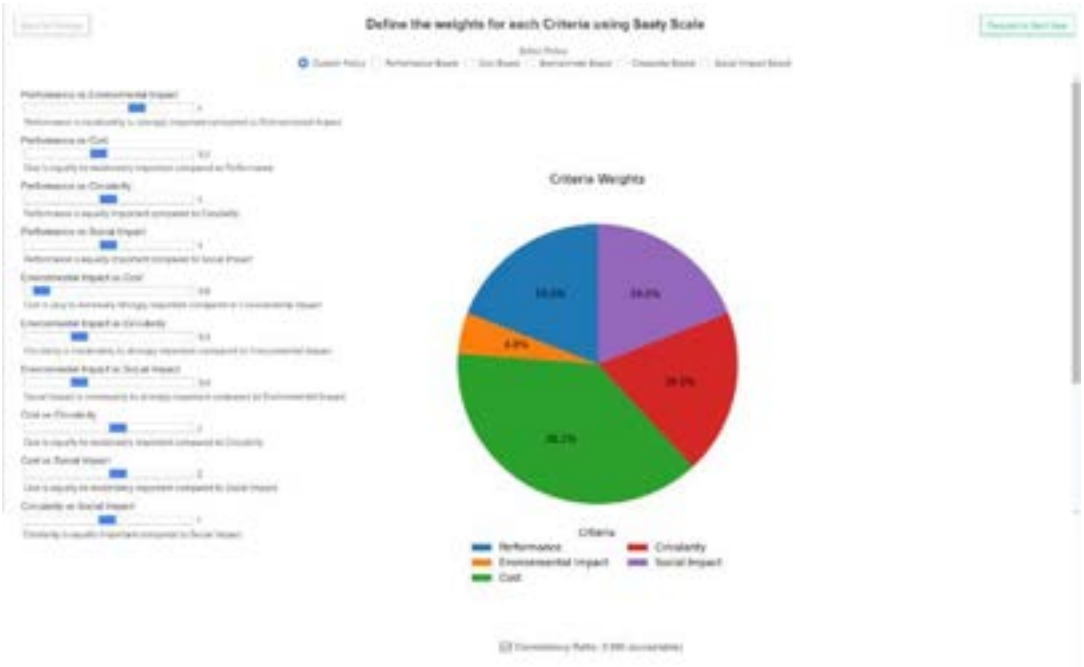


Figure 1. Holistic Sustainability Assessment Tool Interface

Acknowledgement: The present work is being funded by the European Union under GA No. 101191922 (EXAELIA). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Innovation in UAVs: Design, Optimization, Flight Testing and Emerging Technologies

Chaired by:
Prof. Pericles Panagiotou & Prof. Kyros Yakinthos (Aristotle University of Thessaloniki, Greece)

Continuous Bi-directional Trailing Edge Morphing using Hyperelastic Solid Hinges

Jan Tikalsky
German Aerospace Center (DLR), Germany

1. Introduction / Objectives

The reduction of CO_2 emissions from aircraft represents a major challenge. A technical approach to increasing overall efficiency and reducing CO_2 output is the implementation of morphing trailing edges (camber morphing). The potential for efficiency improvement, particularly under off-design conditions, has been demonstrated through both simulations and wind tunnel models. In this context, the elimination of all gaps and steps on the wing skin is attractive.
However, from a structural perspective, this creates a dilemma: the wing skin requires sufficient stiffness to withstand surface pressures without significant deformation, while simultaneously being flexible to keep actuation requirements low. Existing solutions often achieve this by either discontinuing the skin structure on the underside or utilizing elastomeric skin materials. This work presents the design and experimental validation of a concept that realizes a fully gap-free wing capable of varying camber along the span without geometric or material discontinuities on the airfoil surface.

2. Methodology

Based on the authors' prior work, HyTEM is established as a skin-structure concept . This concept was initially investigated on a single airfoil section in. Building upon this foundation, the present study addresses spanwise differentiation. As illustrated in, non-uniform deformation of airfoil sections along the span induces length variations and curvature gradients in the trailing-edge skins.

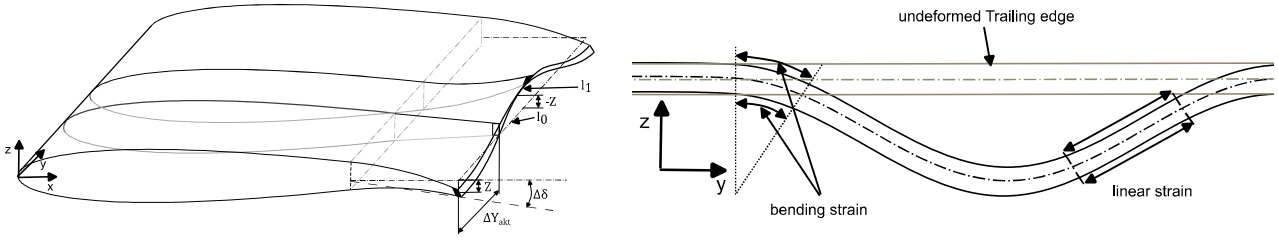


Figure 2: *Skin strains due to nonlinear spanwise deflections.*

The required mean strains are initially determined analytically using an assumed deformation function. The resulting high spanwise strains are compensated via corrugations, eliminating the need for material transitions or structural slits. To identify an optimal geometry, a parameter study employing a recursive Finite Element Method (FEM) is conducted to determine the allowable global strain for each configuration. Leveraging the identified geometry, a wing-section demonstrator equipped with five actuator stations is designed and simulated under various deformation cases. Subsequently, the simulated deformations and required actuation forces are validated against experimental data.
Finally, both the HyTEM- and a conventional-wing design are evaluated on "Proteus," a UAV operated by the DLR – German Aerospace Center, through scaled flight tests. This enables a direct comparison of both concepts under realistic flight conditions. Since Proteus cannot replicate transonic aerodynamics due to its maximum flight speed, the present analysis initially focuses on applicability to subsonic aircraft. The Proteus configuration has been adjusted to match typical general aviation aircraft in terms of Reynolds and Mach numbers, as well as wing loading.

3. Results / Conclusions

A parameter study optimized a continuously morphing wing configuration for significant spanwise differentiation with minimal surface area increase. Segment tests validated simulation models with less than 2.7% discrepancy in deformation forces and under 2 mm geometric deviation. Subsequent flight tests on a seamless, ten-actuator wing design demonstrated a 50% increase in roll rate while using only 30% of the structural deformation limit. Actuators remained well within capacity, showing just 44% utilization even at a load factor of 5.7g. These results confirm the feasibility of flight-testing bi-directional morphing wings under realistic conditions. Future work will focus on adapting this technology for commercial aircraft and quantifying its impact on overall aircraft performance.

Aerodynamic Performance of Droop Leading Edge Aerofoils at Low Reynolds Numbers

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1. Introduction / Objectives

Small UAVs and MAVs typically operate at Reynolds numbers of $1 \times 10^5 – 3 \times 10^5$, where laminar–turbulent transition and laminar separation strongly control lift, drag, and stall . Droop leading edges (DLEs) have shown potential to alleviate stall in rotorcraft-level applications , but their behaviour in low-Reynolds-number conditions has not yet been fully quantified. In particular, it remains unclear whether the aerodynamic benefits observed on a two-dimensional aerofoil can be translated into performance improvements for a rotating propeller operating under similar Reynolds-number conditions. This study aims to investigate whether a DLE design can delay static stall and improve aerodynamic efficiency for the NACA 0012 aerofoil representative of small aircraft operating conditions. Another objective is to assess whether transition-sensitive Reynolds-averaged Navier–Stokes models can reproduce the observed low-Reynolds-number performance trends and to determine the effective droop magnitude for subsequent rotating propeller investigation.

2. Methodology

Wind tunnel tests were carried out in a TecQuipment AF1450S subsonic tunnel using near-full-span 3D-printed NACA 0012 models of chord 225 mm and span 447 mm. Three configurations were examined experimentally: a baseline aerofoil (δ = 0°) and DLE geometries obtained by drooping the front 25% chord by 10° and 20°. Measurements covered Re = 1 × 10^5, 2 × 10^5, and 3 × 10^5 over −20° ≤ α ≤ 20°. Thirty surface pressure taps were used to obtain Cp distributions; lift was determined by pressure integration and aerodynamic efficiency was evaluated together with wake-based drag estimates using blockage-correction procedures following Ewald et al . Figure 1 summarises the overall methodology adopted in this study, linking the two-dimensional experimental and numerical investigations with the subsequent translation of the selected DLE geometry to a rotating-propeller configuration. Complementary CFD simulations were performed in OpenFOAM for δ = 0°, 5°, 10°, 15°, and 20° to examine droop-magnitude effects beyond the tested geometries. Two transition-sensitive RANS models were compared: the k–kL–ω model of Walters and Cokljat and the k–ω LKE model of Medina et al. . Mesh-independence, inlet-condition assessment, and validation against experimental data were used to judge predictive fidelity in pre-stall and post-stall regimes. The experimental and numerical results were then used to identify the most effective DLE configuration for a subsequent rotating-propeller investigation.

A rotating propeller wind-tunnel campaign is currently being developed to determine whether the aerodynamic benefits identified in the two-dimensional study can be translated into propeller performance under realistic low-Reynolds-number operating conditions. The selected DLE geometry will be incorporated into a propeller blade design and tested over a range of rotational speeds and advance ratios to evaluate thrust, torque and propulsive efficiency.

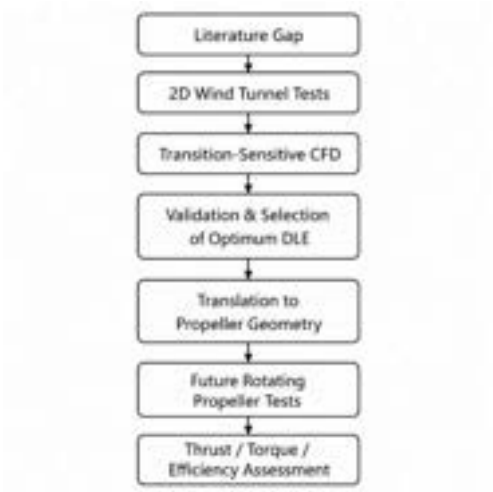


Figure 3. *Overview of the experimental, numerical and propeller-development methodology.*

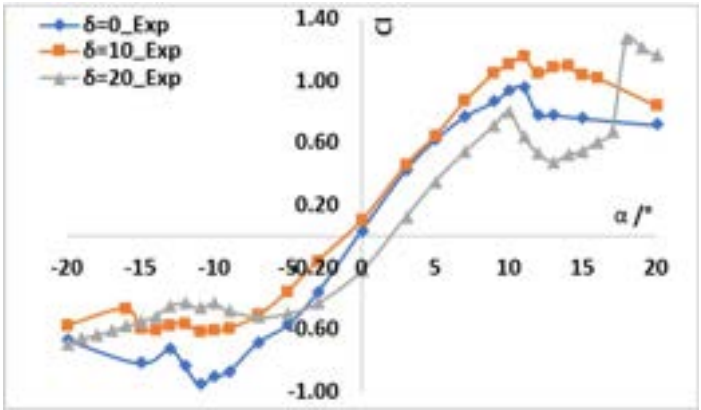


Figure 4. *Lift coefficients for the δ= 0, 10° and 20° NACA0012 aerofoil at Re = 200,000*

3. Results / Conclusions

Moderate droop produced clear low-Reynolds-number benefits. Relative to the baseline

aerofoil, the δ = 10° configuration delaying stall by about 1–3°, increasing maximum lift by roughly 10–20%, and improving lift-to-drag ratio by as much as 3–5 times at pre-stall conditions. Oppositely, excessive droop degraded robustness. A post-stall lift recovery was observed for the δ = 20° configuration at high angles of attack. And δ = 15° numerically, showed stronger transition/separation sensitivity and no reliable efficiency gain. Across the investigated Reynolds numbers, the beneficial trend of moderate DLE remained consistent. Both CFD models reproduced the main aerodynamic tendencies at turbulence intensity ranged from approximately 0.2–1.5%, but the k–ω LKE model showed closer agreement with measured stall onset and post-stall behaviour. The results indicate that a moderate droop leading edge is a promising passive high-lift concept for low-speed applications and provides a sound basis for rotating-blade studies.

Experimental investigation of corrugated airfoils at low Reynolds numbers

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1. Introduction / Objectives

Corrugated airfoils (CAF) can exhibit superior aerodynamic performance at low Reynolds numbers (*Re*) compared to conventional smooth airfoils and flat plates . The Reynolds number range between 10^4 and 10^5 is gaining increasing relevance for technical applications such as Micro Aerial Vehicles (MAVs), thanks to the ongoing miniaturization of sensor payloads and system components. Although some studies exist, there remains a lack of systematic investigations, and uncertainties persist regarding the reliability of numerical predictions . To address this gap, a dedicated experimental setup for low-*Re* airfoil testing is being designed and implemented in the ALFA wind tunnel facility at the ZHAW Centre for Aviation. The overall objectives are to 1) systematically investigate different parameters of CAF geometries and their impact on aerodynamic characteristics, and 2) provide experimental data for the validation of numerical methods.

2. Methodology

The experiments were conducted in the ALFA wind tunnel at the Centre for Aviation. It has a cross section of 600 mm x 900 mm and can reach flow speeds up to 45 m/s. For this study, an experimental setup using splitter plates was designed, so that airfoils with a span of 200 mm can be installed. An external 3-component balance was used for precise force measurements. The inflow conditions were characterized using hotwire anemometry.

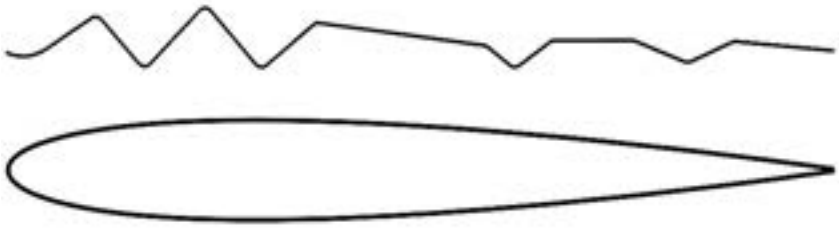


Figure 1. *The geometries of the exemplary CAF (top) and the NACA0012 airfoil (bottom) investigated in this study.*

The desired low *Re* can be achieved by selecting small chord lengths or low flow speeds. Both approaches pose challenges. The former was addressed by developing and critically evaluating various fabrication methods for small-scale CAF. The latter was addressed by successive reductions in flow speed and concurrent uncertainty tracking. The experimental setup was validated with published experimental data for a NACA0012 airfoil. The results were then used for comparisons with a dragonfly-inspired CAF geometry derived from an earlier study . Both airfoils are depicted in Fig. 1. Chord lengths of 50 mm and 100 mm were tested for the NACA0012 and the CAF at identical *Re* in the range $1x10^4$ to $1x10^5$ to find the best compromise between chord length and flow speed. This included determination of aerodynamic characteristics, including the lift curve slope, lift-to-drag ratio, max. lift coefficient and stall behavior.

3. Results / Conclusions

The measurements show good agreement with values reported in earlier work. The S-shape behavior around zero *AoA* of the NACA0012 at low *Re* was reproduced. In contrast, the CAF has a linear behavior up to stall over all investigated Re, as illustrated in Fig. 2. The drop in lift after stall is small compared to that of the NACA0012. For both airfoils, the aerodynamic performance is a strong function of *Re*.

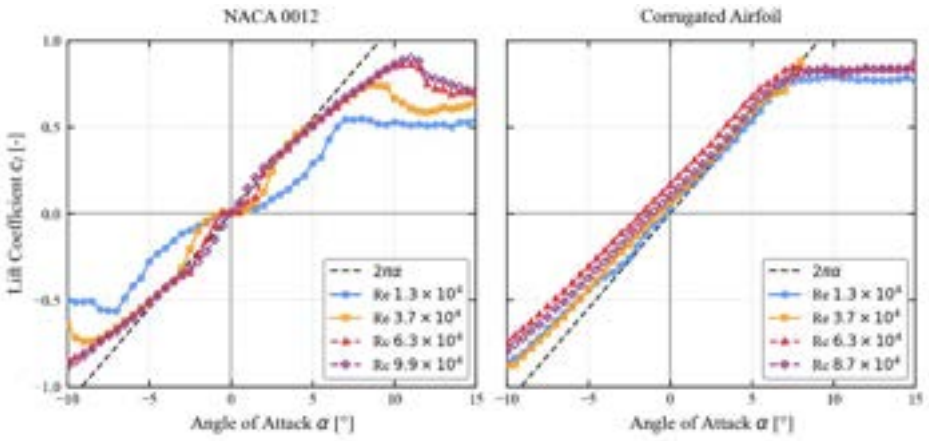


Figure 2. *Lift coefficient over angle of attack for NACA0012 (left) and CAF (right) for Re from 10^4 to 10^5. Chord lengths of 50 mm were used for Re below $5x10^4$, and 100 mm for higher values.*

The airfoils with smaller chord lengths exhibited flutter at higher *Re*, respectively premature stall. Conversely, flow speed fluctuations made measurements at very low speeds impractical. For future experiments with this setup a crossover from 50 mm to 100 mm chord length at a *Re* of $5x10^4$ is therefore recommended.
The experimental setup and procedures were successfully validated. This serves as the basis

for future systematic investigations into the characteristics of corrugated airfoils, their optimization, and the development and validation of corresponding numerical methods.

$\gamma - Re_\theta - SST$ parameter and inflow turbulence condition tuning for corrugated airfoils at low Reynolds numbers

Marius Banica
ZHAW IEFE Institute of Energy Systems and Fluid Engineering

1. Introduction / Objectives

Micro Air Vehicles (MAVs) typically operate at Reynolds numbers (Re) 10^4 - 10^5. This regime has become technically accessible due to the ongoing miniaturization of sensor payloads and system components. Corrugated airfoils (CAF) may offer superior aerodynamic performance at these Re compared to conventional smooth airfoils and flat plates . CAF have been studied experimentally but there continues to be a lack of systematic investigations regarding design parameter choice. Numerical modeling also remains challenging due to complex transition phenomena . The author evaluated the applicability of industry standard turbulence models and the $\gamma - Re_\theta$-SST transition model to CAF derived from in earlier work . Discrepancies were much lower with the transition model but remained noticeable. In this work, various $\gamma - Re_\theta$-SST parameters are systematically tuned to improve outcomes. In addition, inflow turbulence conditions are shown to significantly affect results. LES simulations for selected setups are used for comparisons.

2. Methodology

All simulations were performed using the commercial software ANSYS Fluent 2025R2, which applies a cell-centered finite volume approach to discretize the governing equations. Convective fluxes were evaluated by reconstructing variable values at cell face centers using a second-order upwind scheme, combined with a least-squares cell-based gradient calculation and a minmod-based gradient limiter. Gradients at cell faces were obtained through linear interpolation of cell-centered gradients. Time advancement was achieved using an implicit second order backward differencing scheme, with an algebraic multigrid method employed to accelerate convergence. A pressure-based coupled solver was used to simultaneously resolve the pressure and velocity fields. Convergence within inner loops was defined by a reduction of residuals by three orders of magnitude. Calibrated parameters in the $\gamma - Re_\theta$-SST model included C_{s1}, C_{a1}, C_{a2} and C_{e2}.
The LES simulations were carried out for spanwise extents of 0.2c, 0.3c, and 0.5c, where c is the chord length. A maximum CFL=0.9 was used for the LES, while for the $\gamma - Re_\theta$-SST time step independence was verified for every simulation. Grid design was based on extensive grid independence studies reported in previous work. For all simulations, the maximum y+ < 1 throughout the entire run. For the LES, x+ < 1, z+ < 32, and a synthetic turbulence generator was used to prescribe inflow velocity fluctuations consistent with the turbulence inflow characteristics and the -5/3 drop in the inertial subrange. LES quality was verified by ensuring spanwise decorrelation at strategic locations on the airfoil suction side and in the wake, and by confirming convergence of the spectrum. Aerodynamic characteristics, including the time-averaged lift coefficient, $\bar{c}_l$, drag coefficient, $\bar{c}_d$, and aerodynamic efficiency, $\bar{c}_l/\bar{c}_d$, were determined for angles of attack in the range 0° ≤ a ≤ 8°. The CAF studied is shown in Figure 1.



Figure 1. *Corrugated airfoil used in this study (P4 from).*

3. Results / Conclusions

$\bar{c}_l$ is shown on the left of Figure 2. Experimental data from and numerical data from are given by the red dots and triangles, respectively. The squares, diamonds, and crosses are current results for tuned $\gamma - Re_\theta - SST$ parameters, for the $\gamma - Re_\theta - SST$ model with standard coefficients and modified inflow turbulence, and for the LES, respectively. All modified setups improved predictions. Three causes are identified. First, $\gamma - Re_\theta - SST$ parameters were not calibrated for this type of problem. Second, a maximum turbulence intensity TI=0.6% was reported in , but predictions are in better agreement for TI~1.0-1.3%, which is consistent with experimental uncertainties. Third, the $\gamma - Re_\theta$-SST model did not capture the complex near field. For example, the right of Figure 2 shows Q-criterion iso-surfaces at AoA=2° for the LES. The rapid breakdown of 2d structures is inadequately represented by the $\gamma - Re_\theta - SST$ model.

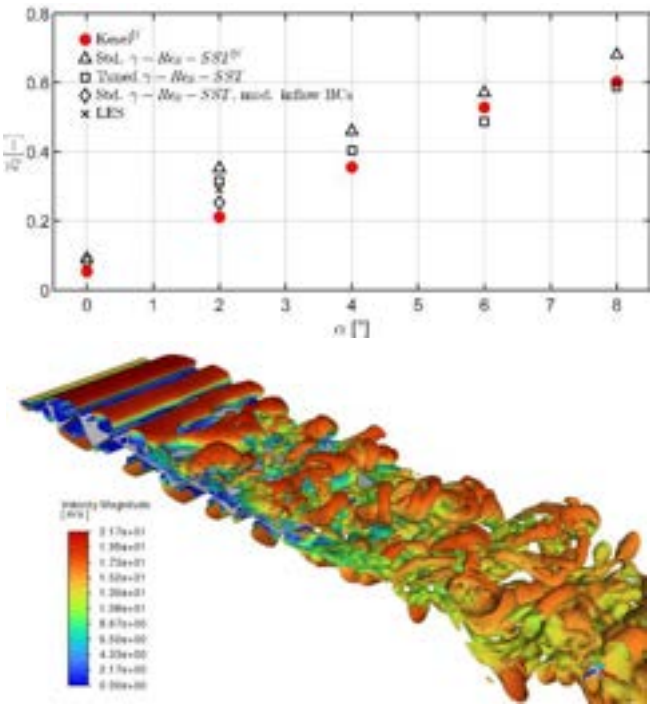


Figure 2. *$\bar{c}_l(\alpha)$ (left) and Q-criterion iso-surfaces for the LES (right), Re=10⁴.*

Performance Investigation of UAV Propellers via Wind Tunnel Testing

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[2] National Technical University of Athens, Greece

1. Introduction / Objectives

This report investigates the performance and efficiency of Unmanned Aerial Vehicle (UAV) propellers through wind tunnel testing. The main purpose of this study is to provide a detailed characterization of propeller behavior, throughout the entire mission profile of a UAV. As initial flight testing results indicated certain discrepancies between experimental results and manufacturer-provided data (APC), it is considered necessary to identify these differences and establish a reliable in-house baseline. A custom-developed thrust stand is utilized, designed to measure static and dynamic thrust, rotational speed (RPM) and key electrical parameters at various angles of attack. The thrust stand is positioned inside a low speed, closed-loop wind tunnel and a comprehensive data collection is conducted, to categorize the propellers and verify their performance.

2. Methodology

The thrust stand (figure 1) is developed at the Laboratory of fluid Mechanics (LFMT) and Turbomachinery, at the School of Mechanical Engineering, at the Aristotle University of Thessaloniki (AUTh), following a comprehensive review of existing literature and similar wind tunnel testing studies. The experiment is conducted in the closed-loop wind tunnels of the LFMT, AUTh (test section 600mm x 600mm) and the Laboratory of Aerodynamics, School of Mechanical Engineering, National Technical University of Athens (test section 1400mm x 1800mm). The freestream velocity varies between 0(static) and 36 m/s at 6 m/s increment, with a turbulence intensity below 1% at both test sections. Concerning the throttle range, measurements are taken at 1000 RPM increment, up to the maximum RPM of each setup. The experimental set up features an adjustable mounting system, which allows the test engineers to adjust the angle of attack between 0°, 3° and 7°. The motor used for all tests was T-MOTOR AT2814 900kv Brushless Motors. Preliminary static testing indicated that the motor's maximum power output restricts the evaluation of larger propeller diameters and prevents them from reaching higher RPM under high load scenarios. Consequently, the propellers selected for examination are limited to diameters not exceeding 13 inches. For data acquisition, a custom-developed data acquisition system is used to record the parameters of thrust, current, voltage, power, RPM and throttle simultaneously, with the air speed measurements provided by the wind tunnel. During the data processing phase, the synchronization and alignment of these datasets are performed.

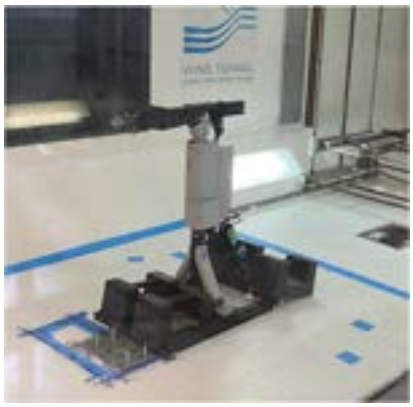


Figure 1. *The thrust stand of AUTh positioned inside the NTUA test section during the wind tunnel experiments.*

3. Results / Conclusions

The resulting data provides a comprehensive mapping of propeller behavior, identifying optimal operating points within specific current and power constraints. As expected, thrust decreases as air speed increases, while current draw peaks at lower air speeds before progressively declining. Propellers with higher pitch sustained thrust levels at higher airspeeds. Although experimental results approach manufacturer specifications in many cases, they did not perfectly coincide. As shown in Figure 2, one propeller closely matches theoretical curves while the other deviates significantly, highlighting that APC data does not always reflect real-world performance. Ultimately, these observations, which will be discussed in the manuscript, form a propeller selection process that meets aerial platform mission requirements within motor and imposed current limits.

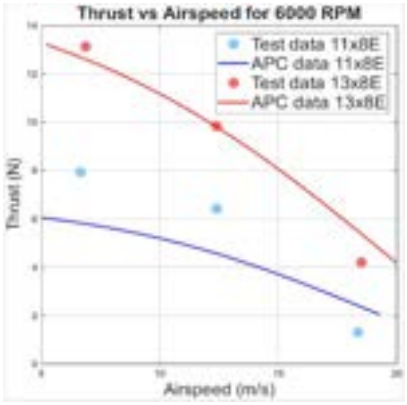


Figure 2. *Discrepancies between APC and experimental data of propellers 11x8E and 13x8E.*

A Fast Design Methodology for eVTOL UAV Propeller Considering Noise Emissions

Jan Šimák, Miroslav Šmíd
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1. Introduction / Objectives

The recent development of eVTOL UAVs introduces new engineering challenges. New aircraft concepts frequently utilize distributed propulsion systems featuring various

configurations of propellers, tilting rotors or tilting wings. Because these vehicles are intended to operate in densely populated areas, minimizing acoustic footprint is of great importance. Consequently, analyzing the hover stage is just crucial as evaluating propeller characteristics during cruise flight. During vertical takeoff and landing, the propeller experiences high aerodynamic loading to generate maximum lift, which adversely affects noise emissions. This paper presents a design method for a low-noise propeller tailored to these vehicles, combining geometric shape optimization with aerodynamic and aeroacoustic analysis. Finally, a propeller demonstrator was manufactured based on the optimized design for experimental verification.

2. Methodology

While thorough aerodynamic and acoustic analyses are time-consuming and unsuitable for preliminary design, a rapid, simplified, yet sufficiently accurate method is ideal for initial propeller geometry definition. The presented tool utilizes the open-source FreeCAD software for geometric modelling, extended by custom modules developed at VZLU Aerospace. These modules allow for the definition of the propeller blade shape via parameters across prescribed cross-sections along the span, such as chord length and pitch angle. The core framework relies on an iterative Blade Element Theory (BET) formulation, which ensures rapid computation with sufficient accuracy, augmented by 3D aerodynamic corrections. Individual airfoils within the cross-sections are defined using a modified 13-parameter Bezier-Parsec parameterization . Optimization of their shape is driven by a microgenetic algorithm. Their aerodynamic characteristics across the required range of angles of attack, Mach and Reynolds numbers are computed using XFOIL, MSES or CFD or could be derived from experimental data when existing airfoils are used.

To evaluate aeroacoustic emissions, a custom Python-base module implements the Ffowcs Williams-Hawkings (FW-H) acoustic model for tonal noise and the BPM model for broadband noise. This module processes the aerodynamic design outputs to rapidly predict noise levels at predefined observer locations. Additionally, it can also work with data from general CFD software, facilitating validation against high-resolution CFD methods.

The design is performed within operational and manufacturing constraints (e.g. trailing edge thickness) and couples aerodynamic and aeroacoustic objectives. The optimized designs are subsequently verified via high-resolution CFD methods.

To demonstrate the practical application of this methodology, a propeller model with a 1.4 m diameter operating at 2,500 rpm was designed, aiming to maximize the Figure of Merit (FOM) in hover while minimizing the Overall Sound Pressure Level (OASPL) in dBA.

3. Results / Conclusions

In summary, this work presents a fast and efficient numerical design tool for eVTOL UAVs propellers, balancing both aerodynamic performance, manufacturing and acoustic constraints. The reliability of the optimized designs was initially confirmed via high-resolution CFD methods. To further validate the methodology, a propeller demonstrator was manufactured. Future work will focus on wind-tunnel and acoustic testing of this demonstrator. Comparing these experimental results with the numerical data will provide

valuable insights into the tool's accuracy and established a framework for low-noise UAV propulsion systems.

Influence of payload on the design of a solar UAV to achieve year round operations

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1. Introduction / Objectives

Solar powered UAVs have practical long endurance applications including surveillance, signals relay, and intelligence gathering. At altitudes below 10'000 ft, current endurance record holders and successful solar powered UAVs feature glider-like, high aspect ratio wings. The record-breaking flights have occurred in summer months where solar irradiance and daylight hours are at a maximum in their respective geographical locations. These configurations are designed for operations in the summer months and are incapable of sustaining long endurance flight at other times of year where there is lower solar irradiance. Operationally, the usefulness of a solar UAV is dependent on the number of days of the year that continuous flight is possible. This paper details the optimization of a clean wing T-tail solar UAV for two different payload cases, maximizing the time spent at a full State Of Charge (SOC) for different months, improving the operational capabilities of the UAV.

2. Methodology

There are several models and design tools involved in modelling and simulating the performance of a solar UAV for this optimization. The aerodynamics, propulsion, stability, weight, and balance are analyzed using models developed in *pyACDT*. The weight prediction for small UAVs was developed specifically for this project, generating empirical relationships from databases of small electrical propulsion components and a fully stressed beam equation for the weight prediction model of lifting surfaces.
For a given geometry, the weights, stability, propulsion, and aerodynamic characteristics are used to simulate a flight for the UAV as a 3-degree of freedom point mass. The recharging of the batteries uses a solar model based on the solar irradiance and sun position . The flight begins at sundown and is flown in a circular trajectory until the vehicle has flown for 24 consecutive hours or the battery SOC has depleted to 30%, whichever occurs first. Figure 1 shows the SOC and available, collected, and required power of a sample vehicle with the definition of the charge margin, t_{cm}.
The objective function is the cumulative flight time and charge margin for four individual flights, where each flight is simulated on the solar equinoxes and solstices. A higher objective function value will have more days of the year where continuous flight is possible, which increases the robustness to in-flight disturbances that cause fluctuations in the available or collected solar power or the power draw of the UAV, thanks to the higher charge margins and low base-line power draw. The optimal geometry is found using a global optimizer to maximize the objective function value, also referred to as the fitness. Design variables include wing, fuselage, and empennage geometry parameters, the size and orientation of the solar array, motor type, propeller type, and size of battery packs. The constraints are defined to ensure the design space consists of feasible and realistic configurations to comply with ground handling, manufacturing, and stability limitations. The solar UAV is optimized for two distinct representative payload cases.

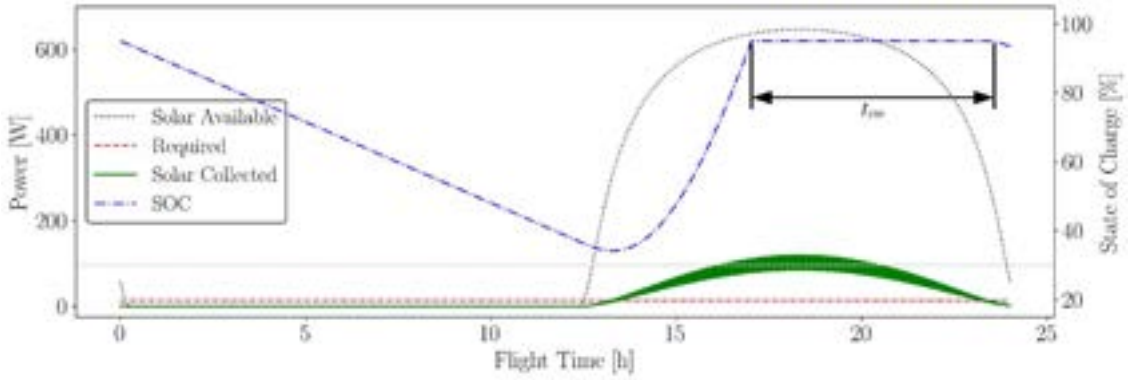


Figure 1. *Power curves and SOC throughout a simulated flight.*

3. Results / Conclusions

The resulting geometries for both payload cases show the physical and energetic differences required to accommodate the different weights and power draws, showing the necessary tradeoff between onboard energy capacity and flight time. The energy capacity must be sufficient to accommodate the power draw of the payload and propulsion system but not excessive enough to unnecessarily increase the weight and therefore power draw, leading to a decrease in fitness. At higher payloads, increasing the span increases the fitness of the UAV at the expense of additional challenges to manufacturing and ground handling. There is a distinct tradeoff between flying at the minimum drag speed and the maximum propulsive efficiency speed if they are not equivalent, emphasizing the importance of synchronizing the airspeeds for maximum aerodynamic and propulsive efficiency, allowing for larger charge margins and longer endurance.

Drive Train Architectural Considerations and Design for the DLR High-Altitude Platform

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1. Introduction / Objectives

High-Altitude Platform Stations (HAPS) are a growing technology with the potential to replace satellites partly with these cheaper and environmentally friendly solar-powered aircraft. A central system of a HAPS is the drive train, which includes all energy-related systems such as the propulsion, battery, solar generator, and power distribution.
Each system's weight and positioning have a large influence on the overall aircraft design and performance, which makes its design strongly interdisciplinary. The main challenge is to reduce the weight while fulfilling the functions and performances and coping with the environmental conditions of the stratosphere.
The DLR-owned High-Altitude Platform (HAP) research project was launched with the aim of building a HAPS for the operation in the lower stratosphere. This publication presents the design approach of the HAP drive train from the identification of the relevant requirements and design restrictions over to the development of a system architecture to specific design decisions made.

2. Methodology

The HAP project was planned and documented using model-based systems engineering

(MBSE). The development of the overall system and the subsystems followed the V-model approach. From the overall aircraft requirements several functions were allocated to the drive train system. This includes the generation of the required thrust for flight, storing electrical energy, generation of electrical energy from the sun, recuperate potential energy of the aircraft, and distributing electrical energy to the avionic consumers and payload. The system requirements were clustered and allocated to subsystems according to the principle of loose coupling and high cohesion. The drive train was divided into six subsystems being the propulsion, batteries, solar generator, power distribution, maintenance panel and decentralized temperature measurement system.
The design of the drive train had to be closely coordinated with other disciplines such as the structure and aeroelastic as the positioning of the devices and resultant weight distribution has a large influence on the center of gravity of the aircraft and resultant structural loads. Furthermore, additional design restrictions apply for example the rib spacing determines the size of the solar generator strings which directly defines their operating voltage. In addition, an Electrical Load Analysis (ELA) had been performed to assess the required electrical energy provision for the desired mission profile.
To increase reliability, it was decided to integrate two independent drive trains, for the right- and left-wing halves each capable of supplying the essential avionic consumers. To optimize the system weight several architectural design decisions were made for example the selection of an unregulated power bus eliminating the need of additional DC/DC converters, integration of the Maximum Power Point Tracker (MPPT) into the Battery Management System (BMS), selection of a common communication bus, optimized cabling in terms of lengths and cable diameters, integration of the temperature measurement function into existing devices.

3. Results / Conclusions

The main results of this study are the identification of the main design restrictions and requirements which apply to the design of drive train system for HAPS. Dependencies to other design disciplines such as structure, flight physics and avionics are identified and resultant design restrictions derived. Furthermore, the relevant analysis performed are exploited and corresponding requirements derived.
A system architecture which fulfills the specific requirements of HAP was developed. Specific design decisions which arose during system design are exploited in detail. Based on the proposed system architecture all electronics of the drive train were designed in-house and adopted to the requirements. Purchased parts were produced or modified according to specifications. This contributes to the design of future HAPS and the construction of corresponding drive train systems addressing key architectural considerations which arose during system design process.

Energy harvesting from atmospheric vortices

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1. Introduction / Objectives

Several UAV applications (from loitering ammunitions to pseudolite) require very long range/endurance (several days / thousands of miles). One solution to the associated energy challenge is to extract energy from the atmosphere itself. Birds and gliders are known for

extracting their energy from vertical currents due to orographic effects or thermal convection, but these are limited to narrow areas and specific conditions. On the other hand, albatross can travel thousands of miles , using vertical gradients of horizontal wind in the oceanic atmospheric boundary layer. This "dynamic soaring" has been largely studied and modeled . Although available over large oceanic areas it is constrained to a few meters above sea level. Our objective is to demonstrate that energy can be harvested from medium scale vortices, a structure widely spread in the turbulent layers of the atmosphere, from low altitude to the vicinity of jet streams at high altitude.

2. Methodology

Atmospheric energy harvesting from the oceanic boundary layer has been studied by trajectory optimization using proprietary tools or more common ones as AMPL . We have chosen to use the Python libraries Open MDAO and its associated trajectory optimization package Dymos . They offer a very modular approach for the models and there derivative, allowing to develop, validate and implement independently several UAV flight dynamics models, wind field models, and various energy metrics models. The possibility to use analytic derivatives, in particular the null ones is particularly interesting when using solvers adapted to large sparse Jacobian matrices like SNOPT. Dymos uses pseudo-spectral method to solve the motion Ordinary Differential Equations and find the optimal trajectory as a single optimization problem.

The flight dynamic model used is a classic point mass model expressed in the earth fixed inertial reference frame where lift coefficient, aerodynamic bank angle and thrust fraction are control variables. The three-dimensional wind value is an input to the model.

The wind models are stationary and described in the earth reference frame. Canonical models from the literature are used to validate the optimal trajectories, and a new wind vortex model is introduced. This last model is derived from Winckelman's vortex model , initially developed for aircraft trailing vortices. The choice of Winckelman's is motivated by its fidelity to wind tunnel experimental data, and the derivability of its analytical formulation, with no singularity at the boundary nor the center of the viscous core of the vortex. The model is a 2D one, with an infinite axis. The direction of the axis can be chosen arbitrarily.

The energy model allows to compute different energetic metrics, including both the instantaneous power and the cumulative energy. As both are considered in the literature , we compute the total energy in the earth inertial reference frame and in the air non-inertial reference frame. We also introduce a new metric which is the mechanical energy extracted from the atmosphere.

3. Results / Conclusions

This study allowed us to demonstrate that it exists at least one gliding (with no thrust) trajectory passing through a vortex with a vertical axis (so such that there is no vertical component in the wind) providing an increase in the total energy computed in the earth reference frame. This demonstrate that it is possible to extract more energy along the trajectory than the one dissipated by the drag along that same trajectory.

System Identification of a Lifting Body Fixed-Wing UAV Under Data Quality Constraints

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1. Introduction / Objectives

Beginning in 2018, the Fachhochschule Wiener Neustadt (FHWN) Aerospace Engineering group developed a conceptual design for a cargo transport drone which was subsequently used as the basis for a 12 kg scaled flight demonstrator model named Trogon. A photograph of the scaled flight demonstrator can be seen in Figure 1 below.



***Figure 1**: Photo of Trogon, FHWN's custom-designed and hand-fabricated drone*

To develop the Trogon drone as a research platform, a dynamic and aerodynamic model must be extracted through system identification to enable simulation-based testing. Techniques to achieve this have been addressed in literature, recently in works by Løw-Hansen et al., Matos and Marta, Simmons et al., and Matt et al. In contrast to the UAVs examined in those works, Trogon has simple avionics whose data logging sample rate is much slower than is standard for system identification. This work will present system identification results for Trogon where the aircraft states are estimated using an off-line Kalman filter.

2. Methodology

During flight tests, a human pilot will perform classic control inputs/flight test maneuvers (i.e. step inputs, doublet inputs, etc.), in the longitudinal and lateral-directional axes. Flight test data will be collected through various sensor packages. A JETI Duplex radio/telemetry system record control inputs, body axis angles, rates, and accelerations, as well as airspeed and altitude data. An additional MEMS IMU system will be used to collect additional body axis rate and acceleration data with a higher data sampling rate. Position data in the earth frame will be collected from a GPS sensor. Aerodynamic angles in the wind frame can be estimated using the following relationships:

$$V = \sqrt{u_a^2 + v_a^2 + w_a^2} \qquad \alpha = \arctan\left(\frac{w_a}{u_a}\right) \qquad \beta = \arcsin\left(\frac{v_a}{V_a}\right)$$

where the velocities in the wind frame denoted with a subscript a can be found by subtracting the local wind velocities from the body frame velocities. This will result in collected data in 3 different reference frames. Following the completion of data collection, the aircraft state in the earth reference frame will be estimated by using the GPS data, body axis data, and estimated aerodynamic angles as the basis for an off-line Kalman filter. System identification will then be performed on the filtered states using the time-domain equation error method, as seen in Simmons et al.
Initial flight tests and system identification efforts have already been carried out resulting in transfer function models for single-axis dynamics, such as roll axis dynamics, the output of which can be seen in Figure 2 below.

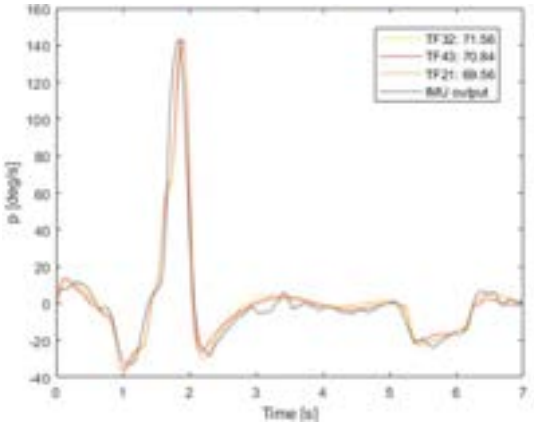


Figure 2: *Outputs from three transfer functions from a aileron step input derived from a previous system identification process.*

However, it was seen during these initial tests that the data quality was not always high enough for the system identification to result in stable models where all transfer function poles had negative real parts. By estimating the aircraft states before performing system identification, the methodology described here should be more robust to poor quality data, allowing for extraction of key dynamic parameters even when subject to large data variances, a high degree of noise, or other uncertainties.

3. Results / Conclusions

The final paper and conference presentation will expand on the methodology described here, present flight paths reconstructed from the flight test data, and present the dynamic model estimated using time-domain equation error method. The methodology's strengths and weaknesses will also be discussed.

Influence of Servo Actuator Power Supply on the Modal Characteristics of an Unmanned Patrol Aircraft during Ground Vibration Testing

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Military University of Technology, Poland

1. Introduction

Ground vibration testing is an essential stage in the experimental identification of aircraft dynamic properties and provides input data for numerical model validation and aeroelastic analyses. In unmanned aerial vehicles, the modal response may be affected not only by the primary load-carrying structure, but also by lightweight, servo-actuated control surfaces. The objective of this study was to investigate the influence of the power supply state of control surface servomechanisms on the natural frequencies and mode shapes of an unmanned patrol aircraft. The main scientific contribution of the work is the experimental assessment of servomechanism energization as a boundary condition during ground resonance testing. Unlike a conventional test configuration, the study compares two physical states of the same aircraft: with unpowered control surface actuators and with actuators powered from an external source, which increases the effective angular stiffness for control surface deflection.

2. Methodology

The experimental investigation was performed on a fixed-wing unmanned patrol aircraft during a ground resonance test. The test campaign was divided into two configurations. In the first configuration, the control surface drive servos remained without electric supply. Under this condition, the movable surfaces were constrained mainly by hinge friction, mechanical linkage resistance, and the passive impedance of the disconnected actuators. In the second configuration, the servomechanisms were supplied with electric power by an external power source. This enabled the actuators to generate the required hinge moment and therefore to restrict the relative motion of the control surfaces with respect to the main airframe.

The aircraft was excited within the frequency range relevant to structural modal identification. The vibration response was measured at selected points distributed over the fuselage, wings, empennage, and control surfaces. The measurement layout was selected to capture both global airframe deformation and local motion of movable surfaces. The recorded response signals were processed to identify the natural frequencies and the corresponding mode shapes for both test configurations. Particular attention was paid to modes involving visible contribution of oscillatory deflections of the ailerons, elevator, rudder, and other servo-actuated surfaces.

The modal parameters obtained for the unpowered and powered configurations were compared directly. The analysis focused on changes in resonant frequencies, differences in deformation patterns, and the level of coupling between the control surfaces flapping and the primary structure oscillations. The applied measurement method allows to take assessment whether energizing the servomechanisms modifies the dynamic behaviour of the aircraft in a way that should be considered during model validation and flutter-oriented analyses. The methodology follows the general principles of experimental modal testing, in which the measured dynamic response is used to determine resonant frequencies, modal damping, and natural mode shapes . In the context of aircraft structures, such experimentally identified modal data are particularly important for assessing the airframe's aeroelastic properties. They can also be used to fine-tune selected parameters of structural FEM models applied in multivariate numerical flutter analyses .

3. Conclusion / Results

The comparison of both test configurations showed that powering the servomechanisms had a measurable influence on the modal characteristics of the aircraft. When the actuators were energized, the control surfaces drive became effectively stiffer and their flapping motion was reduced. As a result, selected natural frequencies increased in comparison with the unpowered configuration. The largest changes were observed for local and coupled modes with significant contribution of movable surfaces flapping, whereas global bending and torsional modes of the airframe were less affected. The results confirm that the power supply state of servo-actuated control surfaces should be treated as an important boundary condition during ground resonance testing. Including this effect can improve the reliability of modal identification, numerical model validation, and subsequent aeroelastic or flutter analyses of unmanned aircraft.



Figure 1. *UAV on the lab stand configured for ground resonance testing.*

Strength analysis of the structure of an unmanned water surface - aerial platform that utilizes the wing in the ground effect made of composite materials

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[2] Air Force Institute of Technology, Poland

1. Introduction / Objectives

The aim of the research is to develop a demonstrator of an unmanned platform utilizing the wing in ground effect to support the special forces operations in maritime environment. One of the main components of the research is the analysis of the platform's structure based on the composite materials used. The analysis of the strength of the platform's structure, made of composite materials, involves determining the structural strength characteristics for the platform's key motion phases.

2. Methodology

The strength analysis of the platform structure (Figure 1) was conducted in accordance with the established requirements. The analysis was performed for the calm water conditions and

for operating conditions below 2°B. A further analysis will address the higher sea states. From a design perspective, the platform hull was divided into five structural modules: the main (middle) hull, starboard lateral hull with a winglet, port lateral hull with a winglet, rudder and elevator, and the propulsion module. The strength analysis of the platform structure was conducted for the takeoff, flight, and landing phases. The platform loads were determined by taking into account the changes in the platform hull's aerodynamic drag, buoyancy of the hydrodynamic hull, and the aerodynamic hull's lift forces based on the average and maximum external load values . The propulsion system thrust and load inputs were also considered. The slamming effect during the high-speed launching were taken into account. The research method involved the strength analysis of the platform structure for previously determined platform loads, parameters, and characteristics of the composite materials used for the platform structure. The finite element method (FEM) was used to analyse the platform's strength . The computational model was based on a flat plate model. The basic Kirchhoff model was used to perform the mathematical modelling of phenomena. The bending moments and the plate's bending stiffness were defined. The differential equations for the deflected plate deformations were adapted and solved according to the 3D model of the platform geometry. The calculations were performed for a carbon fiber composite. The composite material definition for each element of the platform structure was performed within the computational model pre-processor. By defining the element orientations in space and the fiber orientation directions of the individual layers, a resultant laminate group have been obtained. Its physical properties were determined, which are the basis for the analysis. The maximum stress and maximum strain criteria were used to assess the strength of the platform structure, as well as the Hill criterion for comparison purposes.

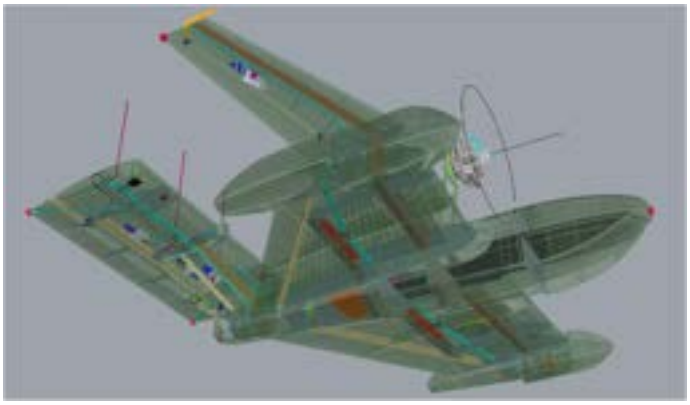


Figure 1. *A general view of the platform structure.*

3. Results / Conclusions

The analysis of the platform's structure strength enabled to develop the detailed design of the technology demonstrator. For initial simulations 3D software was used . Based on the detailed design, a 1:1 scale platform structure called Drozd was manufactured. That demonstrator structure was tested in a strength cage. After the platform integration process is completed the platform will be tested in conditions close to reality. The results of those tests

will be the background for the platform's technical documentation. Despite of this the operational assumptions will be developed and submitted.

Acknowledgement: This research was funded by the National Centre for Research and Development of Poland, grant number 535053.

Airframe Multidisciplinary Design, Analysis and Optimization in Early Design Stages Using a Standardised Parametric Aircraft Description

Ögmundur Petersson, Dr. Sebastian Deinert
Airbus Defence and Space GmbH, Germany

1. Introduction / Objectives

The aviation industry faces complex challenges in civil and military applications which are difficult to address using conventional design processes. Significant increases in performance requirements of aircraft and systems can only be met with unconventional configurations, new propulsion concepts and system architectures, for which limited historical data for statistical predictions are available. Rapidly changing operational requirements lead to shorter design cycles, increasing the need for quick feedback from engineering disciplines to the overall aircraft design process. A multidisciplinary analysis and optimisation (MDAO) framework has been developed at Airbus Defence and Space to address these challenges, especially for airframe structural design. Using a standardised parametric description of the aircraft, disciplinary analysis and optimisation models are created, updated and kept consistent in an automated process. Structural sizing is performed using specialised in-house optimisation tools considering the large number of load cases in industrial application and the specific criteria of aircraft structural design.

2. Methodology

The framework supports several aircraft structural design use cases:

- **Fast structural sizing for early mass estimations**: Starting from a first aircraft conceptual sketch, analysis meshes for the structure and potential theory aerodynamics are generated. Manoeuvre loads are calculated from automatically generated trimmed flight conditions, the structure is sized as a constrained mathematical optimisation problem resulting in a physics-based structural mass estimate.
- **Aircraft concept parameter studies**: The standardised parametric aircraft description is used to create a number of variants (e.g. different wing spans, aspect ratios or structural layouts) and their corresponding analysis models sized and compared according to selected figures of merit.
- **Multidisciplinary shape and sizing optimisation**: Based on the geometric description in the aircraft parametric database, shape design variables (e.g. section chord length, twist, wing span) are defined in combination with structural sizing variables and the corresponding analysis meshes are morphed repeatedly throughout the optimisation in a combined shape and sizing optimisation.

The framework comprises several Airbus Defence and Space in-house tools developed specifically for this task. Descartes performs geometry modelling and analysis model generation. The tool is based on the open-source technologies CPACS[1] and TiGL developed by the DLR (German Aerospace Centre). The main purpose of Descartes is to reduce the time

between devising an aircraft concept and performing physical analyses of varying fidelity on it while keeping the link to the parametric description of the configuration stored in CPACS to enable wide varieties of parameter studies. Descartes includes a graphical user interface for interactive design as well as a Python interface for automated workflow applications. Lagrange[2] is a full-featured linear finite element solver including semi-analytical sensitivity analyses of all nodal and elemental results with respect to structural sizing parameters. It can be used as a stand-alone tool or as part of a coupled analysis or optimisation framework via its python interface. In addition to traditional structural analysis disciplines, Lagrange contains a comprehensive suite of sizing criteria (strength, buckling, bolted joints, damage tolerance) and manufacturing constraints for aircraft structural design. The architecture of the tool makes the addition of new criteria and determination of their sensitivities easy.

3. Results / Conclusions

The paper presents several successful applications of the tool chain to various application cases, both military and civil. Details of the tools' capabilities and implementation of certain functionalities are explained using real world examples of their application. These include a structural layout study, comparing several different internal layouts sized to the same flight conditions, a coupled shape and sizing optimisation and a full aircraft structural sizing with a large number of load cases and constraints. Comparisons are made to more traditional design processes and an outlook of upcoming developments given.

Surrogate-Based Aerostructural Optimization of a Composite Low-Reynolds-Number UAV Wing

Spyridon Kilimtzidis[1], Eleftherios Nikolaou[1], Panagiota Kelverkloglou[1], Vaios Lappas[2], Vassilis Kostopoulos[1]

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[2] National and Kapodistrian University of Athens, Greece

1. Introduction / Objectives

The aerodynamic efficiency and structural performance of UAV wings are strongly coupled, particularly in low-Reynolds-number applications where lightweight composite structures and high-aspect-ratio configurations are commonly employed. Although numerous studies have focused on aerodynamic optimization independently, fewer works have integrated high-fidelity aerodynamic and structural analyses within a unified framework suitable for preliminary aircraft design. In addition, the high computational cost associated with coupled CFD-FEM analyses often limits their use in multidisciplinary optimization problems.

The present work proposes a surrogate-based aerostructural optimization framework for the preliminary design of a composite low-Reynolds-number UAV wing. The framework combines high-fidelity Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) analyses with Kriging surrogate models and an Expected Improvement (EI) strategy to efficiently explore the coupled design space. The objective is to maximize aircraft range while satisfying aerodynamic, strength, and buckling constraints.

2. Methodology

The proposed optimization framework integrates CFD and FEM analyses within a surrogate-based optimization (SBO) environment for the aerostructural design of a composite UAV

wing. The optimization objective is the maximization of aircraft range while satisfying aerodynamic and structural constraints related to lift, strength, and global buckling. The aerodynamic analyses are performed using a high-fidelity RANS-based CFD solver by solving the Reynolds-Averaged Navier–Stokes (RANS) equations coupled with the Spalart–Allmaras turbulence model . The CFD simulations are conducted under low-Reynolds-number operating conditions representative of UAV cruise flight. The resulting aerodynamic loads and pressure distributions are transferred to the structural model through a one-way coupling strategy. The structural analyses are performed using a high-fidelity finite element structural model using shell and beam finite elements representing the skins, spars, ribs, spar caps, and stringers of the wing. Composite laminates based on the Hexcel IM7/8552 material system are considered for the wing structure. Linear static and global buckling analyses are performed in order to evaluate structural feasibility. The design space includes aerodynamic variables such as aspect ratio, taper ratio, sweep angle, and tip twist, together with structural variables related to spar locations, rib spacing, stringer spacing, and component thicknesses. Latin Hypercube Sampling (LHS) is initially employed to generate the Design of Experiments (DoE). Kriging surrogate models are subsequently constructed for the objective and constraint functions, while the Expected Improvement (EI) criterion is used to identify new infill points during the optimization process . Five independent SBO runs are performed to assess the robustness and repeatability of the framework. Each optimization cycle includes geometry generation, CFD analysis, pressure transfer to the FEM model, structural analysis, surrogate model updating, and constrained infill-point generation. The surrogate model accuracy is evaluated using Root Mean Square Error (RMSE) and Leave-One-Out (LOO) cross-validation metrics, ensuring reliable approximation of the high-fidelity responses throughout the optimization process. The overall CFD–FEM surrogate-based optimization workflow is illustrated in Figure 1.

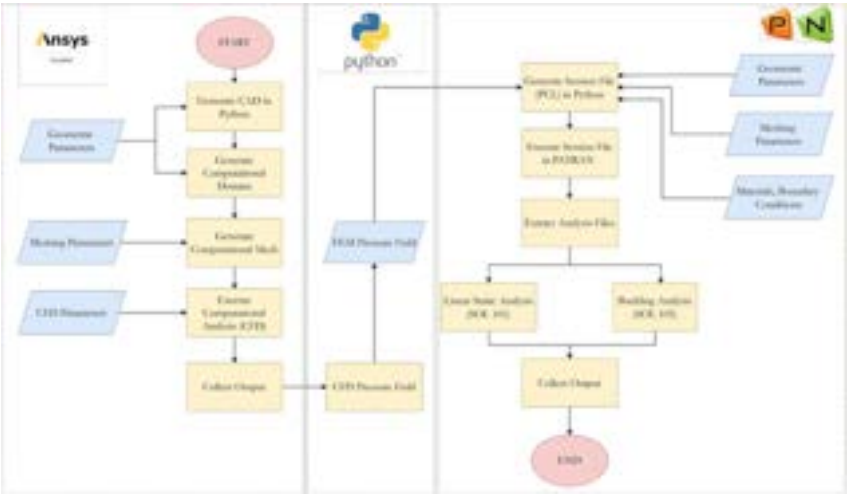


Figure 1. *CFD–FEM surrogate-based aerostructural optimization framework for the composite UAV wing.*

3. Results / Conclusions

The proposed CFD-FEM surrogate-based optimization framework successfully converged toward feasible high-performance wing configurations across all five optimization runs. The

surrogate models demonstrated satisfactory predictive capability, with consistently low RMSE values and stable Leave-One-Out cross-validation results.
The optimized wing configuration achieved a maximum range of approximately 203 km while satisfying all aerodynamic and structural constraints. The results showed that aerodynamic variables, particularly aspect ratio and tip twist, are the dominant drivers of range performance and lift-to-drag ratio improvement. In contrast, structural variables, especially skin thickness, strongly influenced structural feasibility and the definition of the feasible design space.
Overall, the proposed framework demonstrates that high-fidelity aerostructural optimization can be efficiently applied during the preliminary design stage of low-Reynolds-number UAV wings through surrogate modeling techniques. The methodology provides a computationally efficient and robust tool for multidisciplinary UAV wing design applications.

Applicability of Graph Neural Networks for Surface-Field Prediction of Subsonic UAV Wings

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1. Introduction / Objectives

Rapid aerodynamic assessment is important during the conceptual and preliminary design of fixed-wing Unmanned Aerial Vehicles (UAVs), where multiple candidate geometries must be evaluated over varying operating conditions. Reynolds-Averaged Navier–Stokes (RANS) Computational Fluid Dynamics (CFD) provides detailed aerodynamic information, including surface pressure and wall-shear distributions, but its cost limits its direct use in large design-space exploration.
Most aerodynamic surrogate models focus on integral coefficients, such as lift and drag, while surface-resolved quantities contain richer information on local loading, separation-prone regions, and geometry-dependent flow behavior. This work investigates the applicability of Graph Neural Networks for predicting CFD-derived aerodynamic surface fields on subsonic UAV wings. The objective is to assess whether mesh-based graph representations can support accurate field prediction on unseen geometries, while preserving the spatial information required for aerodynamic interpretation and future design optimization.

2. Methodology

The dataset is generated using an automated CFD workflow previously developed by the authors for fixed-wing UAV wings. The framework produces parametrized wing geometries, constructs CFD meshes, and executes steady RANS simulations over a specified range of angles of attack. The current database contains 7,000 wing geometries, with each wing simulated from −4 deg up to either stall or 22 deg, using 2 deg increments. The resulting database provides surface pressure and wall-shear information over a broad design space, including both conventional and blended-wing-body-like planforms across most subsonic UAV categories as classified by NATO.
The present study focuses on a controlled subset of 100 representative wing geometries to evaluate graph-based learning directly on high-resolution CFD meshes. The subset is divided at the geometry level into 70 training wings, 20 validation wings, and 10 test wings, ensuring that all angle-of-attack cases belonging to a given wing remain within the same split. This prevents leakage of geometric information between training and testing. Each sample

corresponds to a wing geometry and operating condition, and the learning target is the nodal distribution of aerodynamic surface quantities, primarily pressure coefficient and skin-friction coefficient components.
The wing surface is represented as a graph whose nodes store local geometric and flow-related descriptors, while edges encode surface connectivity. The investigated architectures include Graph Convolutional Networks, Graph Attention Networks, Message Passing Neural Networks, and U-Net-style graph architectures. The purpose of the comparison is not only to identify the most accurate model, but also to assess how different message-passing mechanisms behave for surface-field prediction under limited training data.
All architectures are conditioned on global design and operating conditions through Feature-wise Linear Modulation (FiLM) . In this formulation, global features are encoded into a latent representation, which is mapped into scale and shift vectors that modulate each message passing layer. This allows local message passing to depend explicitly on the global aerodynamic state, instead of relying only on concatenated nodal and global inputs. Model evaluation is performed on unseen wing geometries and considers nodal errors, field-level behavior, computational cost, memory requirements, and sensitivity to graph resolution.

3. Results / Conclusions

The study is framed as an applicability and benchmarking investigation rather than as a finalized universal surrogate claim. Initial experiments establish the graph construction pipeline, training stability, geometry-level data splitting, and evaluation metrics. The expected contribution is threefold. First, the work evaluates whether graph-based architectures can learn CFD-derived surface fields for geometrically diverse UAV wings using a limited number of training geometries. Second, it examines whether Feature-wise Linear Modulation is an effective mechanism for injecting operating-condition information into graph message passing. Third, it provides a practical comparison between common GNN variants, highlighting the trade-off between accuracy, computational cost, memory demand, and graph resolution. The resulting benchmark supports the development of fast aerodynamic screening tools that retain spatial surface-field information for future UAV design-space exploration.

Aerodynamic shape optimization of airfoils under geometric constraints

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1. Introduction

In conventional airfoil aerodynamic shape optimization methodologies, airfoil geometries are typically deformed over their entire upper and lower surfaces to improve aerodynamic performance . However, due to constraints in practical engineering and manufacturing, often it is desired to constrain the deformation of the airfoil shape in localized regions. For example, it may be necessary to reuse an existing UAV spar configuration where certain parts of the airfoil geometry need to remain unchanged. Such geometric constraints become crucial for limitations such as in small-scale production lines, and in retrofitting applications where an aerodynamically optimized wing is required without major changes to structural components such as spars. Therefore, this study presents an airfoil aerodynamic shape optimization process where localized regions of the airfoil are constrained to a predefined design.

2. Methodology

While the need for geometric preservation in localized regions is heavily dependent on application, for this study, the spar region near the 25% of chord length of the airfoil was used as the geometric constraint.

The study employed Class Shape Transformation (CST) functions for the parametrization of the airfoils, while an in-house developed gradient-free aerodynamic optimization algorithm coupled with XFOIL was used for shape optimization. The geometric constraints were implemented by appropriately defining the CST weights. The objective of aerodynamic optimization was the improvement of aerodynamic performance (C_L/C_D) relative to the baseline airfoil (for this study: NACA 2412, shown in Figure 1).

Three cases of aerodynamic optimization representing different scenarios for the use of geometric constraints were carried out in this study:

1. Case I – the localized spar region (shown by the green box in Figure 1) was constrained to follow the baseline airfoil geometry, representing a retrofitting scenario where geometric preservation is desired.
2. Case II – the localized spar region (green box in Figure 1) was constrained to follow an arbitrarily defined geometry (shown in red in Figure 1), representing a structural/manufacturing constraint while the baseline airfoil is not heavily followed.
3. Case III – an unconstrained case, for comparison.

The optimized airfoils (from the 3 cases) and the baseline airfoil were numerically analyzed using ANSYS FLUENT for final evaluation. The aerodynamic optimization was carried out at a Reynolds number of $2x10^5$, therefore, for the numerical analysis (following a grid independence study), a chord length of 0.29 m and 10 m/sec velocity along with the Transition SST turbulence model was used.

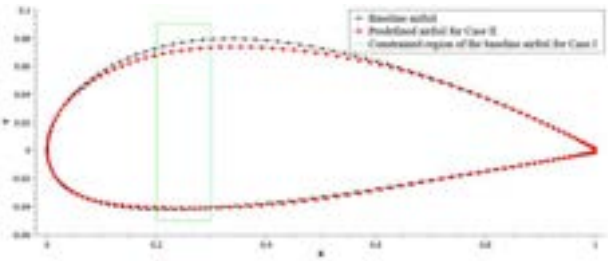


Figure 1. *Baseline airfoil, and the geometric constrains used for Cases I and II.*

3. Results / Conclusions

The resulting optimized airfoil from the aerodynamic shape optimization is shown in Figure 2. The optimized airfoil from the unconstrained case (Case III) shows the maximum deformation, favoring a highly cambered airfoil, while the optimized airfoils from Case I and II are closely matching the defined constraints.

The CFD results for the optimized airfoil from Case III exhibited a maximum improvement of aerodynamic performance of 57% compared to the baseline airfoil. While lower aerodynamic performance gains compared to case III were observed for cases I and II, both airfoils still showed significant improvement in C_L/C_D. Maximum improvements of 35% and 28% for cases I and II were observed, respectively, at lower angles of attack (< 6°).

At mid-to-high angles of attack, however, no significant improvement was observed in both cases. Nevertheless, as many UAVs and conventional aircraft predominantly operate at the lower angles (cruise flight), this study shows the feasibility of constrained aerodynamic shape optimization frameworks.

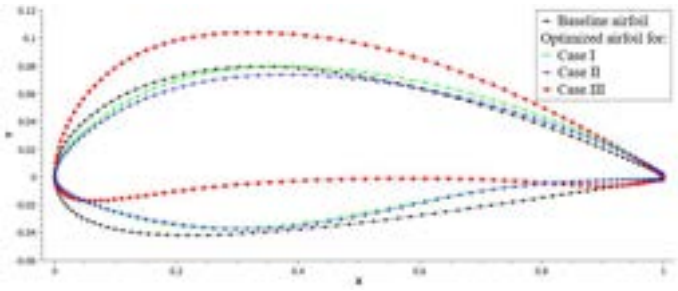


Figure 2. *Baseline airfoil, and the optimized airfoil Cases I, II and III.*

Two-Way Fluid-Structure Interaction Framework for Synthetic Jet Actuator Modelling

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1. Introduction / Objectives

The 2024 Future of Flight Action Plan outlines the UK's investment into zero-emission passenger and goods transport via Short/Vertical Take-Off and Landing (S/VTOL) vehicles . These aircraft incur large drag penalties during steep, low-speed take-off manoeuvres, prompting investigation into active flow control solutions. Piezoelectric Synthetic Jet Actuators (SJAs) periodically ingest and expel fluid to generate a quasi-steady, zero-net-mass-flux 'jet' of successive vortex rings capable of delaying flow separation through localised momentum injection into the boundary layer. Existing CFD models of SJAs approximate the diaphragm motion, neglecting cavity pressures and coupled effects ; whilst the few existing coupled multiphysics models rely exclusively on COMSOL software . Consequently, this study will: (i) develop an alternative fluid-structure-interaction (FSI) modelling approach for quiescent SJA simulation; (ii) validate the model using experimental data from , and (iii) identify steps to extend the framework to crossflow conditions relevant to STOL applications. To-date, transient FEA and CFD simulations have been conducted independently to convergence before attempting co-simulation.

2. Methodology

The investigated SJA is selected to allow direct comparison with the Case 1 results of Gungordu et al. . The piezoelectric diaphragm consists of a single piezoceramic (PZT-5A) layer bonded to a compliant brass substrate. The disc is then clamped within a cavity from which the jet is ejected through an opposite-facing orifice. The cavity and orifice dimensions satisfy the criteria for vortex ring generation, preventing jet re-entrainment during suction. The transient structural response of the diaphragm is modelled in Abaqus (2022) using a dynamic implicit analysis step. The response is assessed under a 20V sinusoidal electric potential applied across the piezoelectric layer, with the input frequency specified via an amplitude curve defining the AC time variation. Abaqus is selected for its high-fidelity

structural modelling capabilities and native inclusion of piezoelectric elements (C3D8E) for fully coupled electromechanical analysis.
The fluid domain is resolved in Star-CCM+ (v2510) using the unsteady Reynolds-Averaged Navier Stokes (URANS) formulation with k-ω SST turbulence modelling. The fluid domain consists of three cylindrical zones representing the cavity, orifice, and external flowfield. The FSI boundary at the cavity base provides an external link for parameter exchange with Abaqus.
Coupling between the two solvers is achieved using the SIMULIA Co-simulation engine in accordance with the procedure illustrated in Fig. 1. At each timestep, Abaqus computes the updated disc deflection considering cavity pressures and traction forces from StarCCM+, which in turn updates the lower cavity surface position within the fluid simulation accordingly. Interrogation of the FSI model will be performed at four discrete actuation frequencies, corresponding to the experimental and numerical mechanical and Helmholtz resonance values in , as a full frequency sweep was deemed computationally prohibitive.

3. Results / Conclusions

A preliminary Abaqus frequency analysis step predicted a first structural resonance of 3302 Hz, compared with the experimentally measured 2950 Hz , with differences attributed to clamping and damping assumptions. An initial transient dynamic analysis driven at 2950 Hz reproduced the expected disc deflection to within 1%, though initial cycles exhibit a varying amplitude envelope, consistent with weak nonlinearities under harmonic excitation away from true resonance. Fluid-only StarCCM+ simulations using piston and moving membrane boundary conditions produced qualitative agreement with , but inconsistent jet velocity predictions. In addition, an anomalous phase offset between cavity pressure and jet velocity was observed near the Helmholtz frequency, as shown in Fig.2. These discrepancies are attributed to the current absence of two-way coupling. The proposed co-simulation framework addresses this by enabling bidirectional data exchange between the structural and fluid solvers at each timestep, and its validation forms the primary objective of the ongoing work.

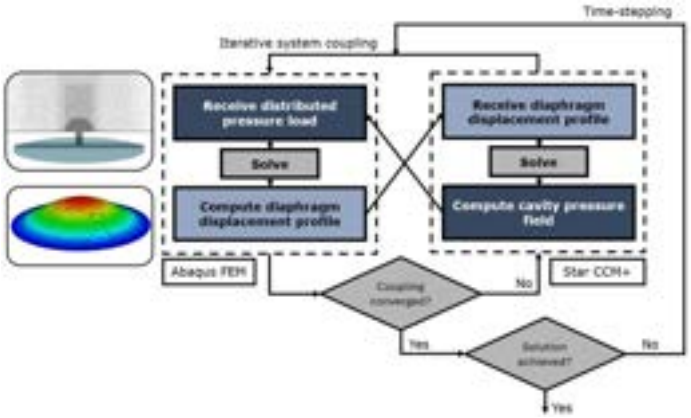


Figure 1. *Co-simulation Coupling Procedure.*

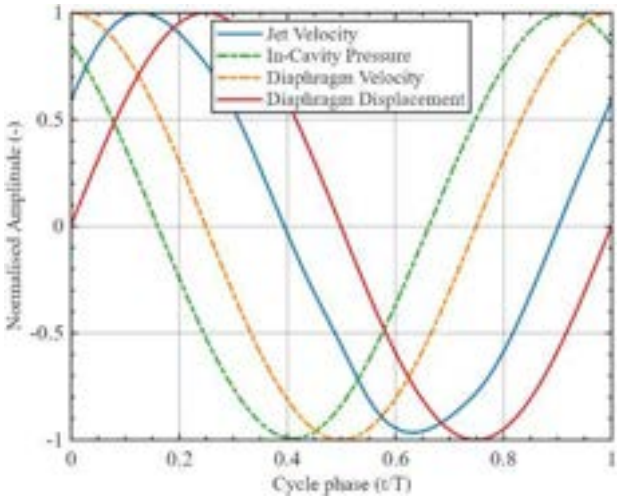


Figure 2. *Normalised response from the fluid-only simulations at 1350Hz driving frequency, using an artificially prescribed diaphragm boundary displacement.*

From Drone to Sports Aerodynamics: A Road to Olympic Medal

Ali Arshad, Dinusha Wijesinghe, Toms Kaidalovs
Riga Technical University, Latvia

1. Introduction / Objectives

Aerodynamic performance and design optimizations are extremely important and play a vital role in high-speed competitive winter track sports like luge, skeleton, and bobsleigh. In winter track sports, especially in luge sports, the differences in milliseconds decide the winners. Additionally, due to the limited area available on the sled for aerodynamic optimizations (as 90% of the area is covered by the athlete's body), the methods available for such optimizations are limited. These limitations lead to restricted conventional large-scale aerodynamic design or surface modifications. In this work, high-fidelity flow control strategies targeted at precise localized surfaces for minimizing aerodynamic drag. The work is supported by the Latvian National Research Program VPP Sports Project under the Latvian Ministry of Education and Science. This research combined the classical flight aerodynamics implemented on drones/UAVs with Unconventional and novel (luge) sports aerodynamics and establishes a high-performance computational optimization framework.

2. Methodology

The study developed a CFD-based numerical framework integrated with comprehensive large-scale experimental validation by wind tunnel testing. The geometry formulation initiates with full-scale 3D scanning of the athletes in sliding configurations, which is subsequently converted into refined CAD models. Numerical simulations were performed in ANSYS CFD modules using ICEM, FLUENT, and CFX. For both cases, a polyhedral grid topology composed of 1.4 million high- density cells and 15 custom prismatic inflation layers to resolve localized boundary layer physics over a 12 m track domain. The grid scheme for luge sports is shown in Fig. 1. Shear Stress Transport (K-ω SST) turbulence model under sea-level air properties at a

freestream baseline velocity of 110 km/h was used for the simulations. For the surface optimizations (for both UAV and luge sports), geometric deformations were executed via a CFD-based adjoint solver linked with Radial Basis Function (RBF) interpolation and an Inverse Multiquadric kernel (smoothness parameter = 5) to dynamically deform mesh nodes across unrestricted Cartesian axes. The optimization specifically isolates critical localized flow-separation regions. The drone/UAV performance was tested through flight tests, while the experimental validations for the luge aerodynamic performance and drag modeling were performed by means of full-scale wind tunnel experiments executed in Dresden, Germany.



Figure 1. *Luge athlete grid scheme.*

3. Results / Conclusions

The adjoint-based surface optimization exhibited significantly improved drag reduction characteristics for both cases. In sports applications (Luge Aerodynamics), the localized surface drag on the seat shell was successfully minimized by 38.8%, leading to a nearly 15% overall reduction in full-scale configuration drag. The results of the flow mechanism confirmed that the mesh deformation (by using adjoint-based solver) delayed boundary layer separation along the seat shell zone towards the athlete's inner thigh edge, resulting in minimizing the flow stagnation at the surfaces. This surface optimization resulted in minimizing the dual-vortex wake into a single streamlined structure. In the flight aerodynamics case (Drone/UAV Aerodynamics), the surface optimization methodology using adjoint-based solver contributed to a 16 % reduction in localized drag at 0° cruise angle of attack. The study provided critical design guidelines of aerodynamic design and surface optimizations for improving the performance of ground and flight-based applications. The Latvian Government's VPP Sports Project, together with conventional aeronautical engineering research, helped solve complicated problems of flow dynamics. This work partially contributed to the performance optimization of the luge athletes, enabling a historic silver medal achievement at the Olympic level for the Latvian national luge team. Figure 2 summarizes the sports and flight aerodynamics.

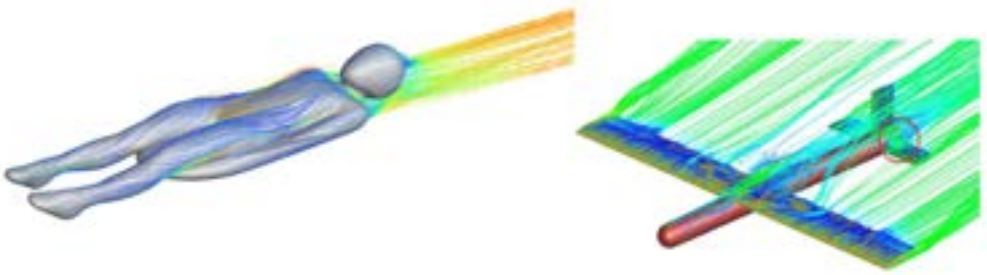


Figure 2. *Sports (luge) and flight (UAV) aerodynamics.*

Fast Lane Drone Development: How Drone manufacturers can easily test their systems without the need of a specific category approval

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1. Introduction

Many drone manufacturers and researchers face long waiting periods of many months when applying for an operational authorization in the specific category. As they have very short development cycles, the waiting periods for operational authorization often disrupt the schedule of these cycles, requiring a decision to either extend the timeframe, try to operate indoors or within the open category, or, as a last resort, operate their system knowingly or unknowingly in violation of the law. Even if an operational authorization in the specific category is already in place, these authorizations are often limited to the specified technical equipment. Article 15 (2) in the Commission Implementing Regulation (EU) 2019/947 may provide a remedy for this issue.

2. Methodology

Since December 2025, there has been established a unique geographical zone (GeoZone) in Germany in accordance with Article 15(2) of Regulation (EU) 2019/947 at the National Experimental Test Center for Unmanned Aircraft Systems operated by the German Aerospace Center. Within the GeoZone unmanned aircraft systems (UAS) can be operated under facilitated conditions, i.e. the UAS-operators confirm that they comply with the requirements of the declaration published at Digital Platform for Unmanned Aviation (dipul) of the German Federal Ministry of Transport . The declaration is based on a simplified risk assessment according the common methodology of the Specific Operations Risk Assessment (SORA) used for UAS-operations in the specific category.
Within the GeoZone, new operational limits apply for UAS operators. All UAS configurations and propulsion types are allowed to operate, also Beyond Visual Lines of Site (BVLOS) and in swarm configurations. While UAS up to a maximum Take-Off Mass (MTOM) up to 600 kg and a maximum characteristic dimension up to 3 m are allowed to operate in the full area of the GeoZone (see Figure 1, red area), vehicles of a characteristic dimension of up to 8 meters and a maximum take-off mass of up to 2,000 kg can be flown in a smaller area (see Figure 1, blue outline). These new thresholds go well beyond the open category and thus enable realistic testing conditions for UAS manufacturers and developers.

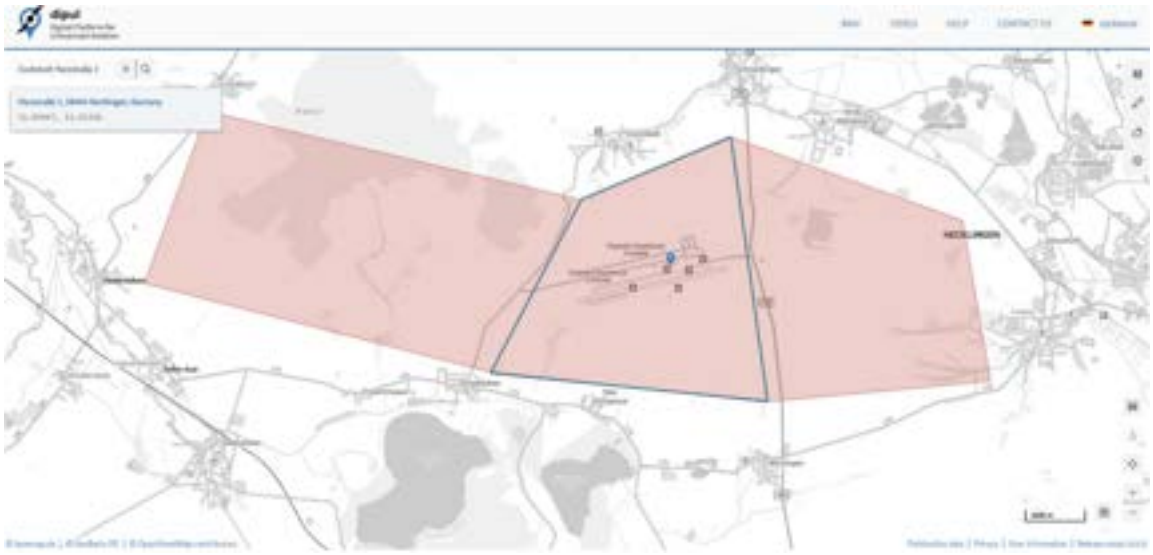


Figure 1. *Full Area (light red) of the GeoZone Magdeburg-Cochstedt and limited area for larger vehicles (blue-outlined) , © GeoBasis-DE / BKG (2025) CC BY 4.0*

3. Conclusions

The GeoZone distinguishes itself nationwide through its uniqueness and its comparatively low requirements relative to an authorization process within the specific category. Since its activation, we have observed a strong interest in the utilization of the GeoZone, particularly from the field of unmanned aircraft system (UAS) development. In this context, it is extremely advantageous to realize shorter development intervals and to test results under real-world conditions. As a result, the developed systems can be validated earlier and more efficiently, and, in cases where development objectives are not met, can be adapted ad hoc, as the regulatory requirements are applied in a pragmatic manner.

A Multi-Criteria Decision Framework for Operational Benchmarking and Capability Optimization of Unmanned Aerial Systems

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[3] University of Patras, Greece

1. Introduction / Objectives

Modern Unmanned Aerial Systems (UAS) are complex, multi-technology platforms whose suitability for dual-use and defense missions is determined by Concepts of Operations (CONOPS) which translate operational needs into various, often conflicting, performance, cost and lifecycle requirements. Selecting or developing a platform that meets these requirements is inherently a multi-criteria problem, further complicated by the interdependencies that link design parameters across subsystems. Traditional Multi-Criteria Decision Analysis (MCDA) practices typically treat criteria as mutually independent and rely

on arbitrary weighting, thereby neglecting both the cascading effects of subsystem modifications and the subjectivity inherent in expert judgement . The present study develops an integrated, advisory decision-support framework that couples AHP (Analytic Hierarchy Process)-derived expert weighting with TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) ranking and parametric interrelations among design variables and propagates uncertainty through sensitivity analyses. The framework's ability to simulate different scenarios and acknowledge expert subjectivity is a significant improvement over current benchmarking practices.

2. Methodology

The framework is an automated structure comprised of a curated UAS database, a set of CONOPS-derived evaluation criteria, and expert inputs, and returns a transparent ranking together with a quantified assessment of its robustness. The criteria are deliberately broader than the performance-oriented sets typically encountered in the literature, in addition to performance attributes, the assessment incorporates functionality, compatibility with existing assets, operator-related factors such as servicing requirements and crew size, and the credibility and reliability of the underlying information sources, including bibliographic, technical and operational references . Each of these dimensions is assigned an appropriate weight within the evaluation framework, so that no aspect deemed relevant by the decision-maker is implicitly discarded. Criterion weights are then elicited from Subject Matter Experts (SMEs) through pairwise comparison matrices on Saaty's 1–9 fundamental scale, from which priority vectors are computed via the principal-eigenvector method. The internal coherence of expert judgement is assessed using the Consistency Ratio (CR), with the conventional threshold of 0.10 used as the acceptance criterion ; matrices exceeding this threshold are returned to the experts for revision before propagation downstream.

The resulting weight vector is then employed within a TOPSIS method, in which the alternative-by-criterion matrix is vector-normalized, weighted, and compared against the positive and negative ideal solutions through Euclidean distances ; the relative closeness coefficient yields the final ranking. Criterion directions are assigned according to the physical meaning of each attribute, so that the ideal and anti-ideal solutions are defined consistently with the operational interpretation of the criteria.

To address the two principal sources of uncertainty in the process, meaning the expert subjectivity in the weight elicitation and the relationships among design variables, two complementary sensitivity analyses are systematically performed . A deterministic one-at-a-time perturbation, in which each weight is varied by a prescribed amount and the remaining weights are rescaled to preserve unit sum, quantifies the marginal influence of every criterion on the closeness coefficient of the leading alternative and on the stability of the top rank. This is complemented by a Monte Carlo analysis in which the weight vector is sampled under multiplicative lognormal noise and the ranking is recomputed over a large number of iterations, yielding the empirical probability that each alternative attains rank one and the dispersion of its closeness coefficient. The same perturbation logic is extended to the parametric interrelations among design variables, so that the cascading effects of candidate subsystem modifications are propagated through the ranking.

3. Results / Conclusions

The framework is demonstrated through two representative case studies, selected to span contrasting operational profiles and design constraints. Expert-derived pairwise comparisons yield consistent weight vectors that pass the Consistency Ratio threshold, and the TOPSIS ranking identifies the leading alternative together with its quantitative margin over the

remaining platforms. The weight sensitivity analyses confirm that the top-ranked alternative is preserved across most deterministic perturbations and Monte Carlo realizations, providing a defensible measure of ranking robustness against expert subjectivity. The propagation of parametric interrelations further reveals that isolated subsystem upgrades yield substantially smaller performance gains than predicted by uncoupled analyses, owing to the cascading effects across the design. Overall, the study demonstrates that integrating expert-driven MCDA with parametric coupling and systematic sensitivity analysis produces materially more realistic R&D and procurement recommendations, while keeping the final decision under human supervision.

Connectivity-Constrained Risk-Aware Planning and Monitoring Framework for BVLOS UAS Operations

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[2] DROMT Srl, Italy

1. Introduction

Beyond Visual Line of Sight (BVLOS) UAS operations are key enablers for advanced drone services in urban and peri-urban environments, but they require the joint assessment of operational risk, regulatory constraints, and communication reliability. In Europe, these missions typically fall within the specific category and require a structured safety assessment according to the SORA methodology . However, operators still lack integrated tools able to combine spatial risk awareness, SORA-related indicators, connectivity constraints, mission planning, and online monitoring.
This work presents a Web-based connectivity-constrained risk-aware planning and monitoring framework for BVLOS UAS operations. The objective is to support operators during mission preparation and execution by integrating multi-layer risk maps, 5G coverage information, SORA 2.5-related indicators, and dynamic path planning within a single decision-support workflow.

2. Methodology

The proposed framework represents the operational environment through a multi-layer grid map generated from heterogeneous geospatial data. The operator defines the area of interest through a Web interface and specifies the mission parameters, including the UAS platform, flight altitude, mission time, and minimum acceptable connectivity level. The selected area is discretized into grid cells, where each cell stores the information required for risk estimation, visualization, and path planning.
The main layers include buildings, population density, ground risk, intrinsic Ground Risk Class (iGRC) indicators, 5G connectivity coverage, and geographical zones. Building information is derived from OpenStreetMap and is used to identify obstacles and estimate the sheltering effect. Time-dependent population data, provided by the telecommunication company WindTre, are used to compute spatially distributed ground risk maps, expressed as expected fatalities per flight hour, following established UAS ground-risk modelling approaches . The same information is also used to provide preliminary SORA-related indicators, including the iGRC.

Connectivity information is provided by WindTre as 5G coverage data and discretized into four levels: not available, poor, good, and very good. The operator can define a minimum acceptable connectivity level, and cells below this threshold are treated as infeasible during planning.
The trajectory planning problem is formulated as the minimization of the cumulative ground risk along the path, subject to connectivity feasibility constraints. The planner is implemented using the Open Motion Planning Library (OMPL) and an incremental sampling-based strategy inspired by RRTX , allowing the trajectory to be updated when the underlying map changes. The Web application is integrated with DROMTHub , which provides telemetry management and mission supervision, enabling online monitoring and dynamic path update.



Figure 1. *Multi-layer Web-based representation of the operational scenario, including mission definition, GeoZone visualization, ground risk, and 5G connectivity coverage.*

3. Results

The framework has been validated through a representative urban use case. The results demonstrate the generation of multi-layer risk maps, the effect of temporal population variations on ground risk, and its impact on path planning. In the considered scenario, a risk-aware path has a length of 1336 m and an average ground risk of 2.52×10^{-6} h^{-1}. After an update of the population density, the path has been updated to maintain a safe route with an average ground risk of 8.54×10^{-7} h^{-1}. The integration with DROMTHub further demonstrated the complete planning–execution–monitoring workflow, including telemetry visualization and dynamic re-planning.
The extended version of the paper will provide additional results highlighting the impact of connectivity constraints on mission planning, as well as further details on the adopted methodologies.



Figure 2. *Online monitoring, including path visualization over*

AltaRica for Small UAS Certification: A Model-Based Safety Analysis Approach to AEP-83

Olivier Cornes, Tatiana Prosvirnova, Christel Seguin
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1. Introduction / Objectives

The rapid proliferation of unmanned aerial systems (UAS) across military and civil domains has created an unprecedented demand for efficient, scalable safety certification processes. NATO's AEP-83 standard provides a structured framework for the airworthiness certification of small UAS, yet the growing complexity and diversity of new systems strain the capacity of classical safety assessment methods such as Fault-Tree Analysis (FTA) or Failure Modes and Effects Analysis (FMEA). While well-established, these approaches are time-consuming and error prone when performed purely manually.

This work investigates the applicability of the AltaRica stochastic event modelling language as a complementary tool to support AEP-83-compliant safety assessments. AltaRica allows for modular design of models and automatic generation of the safety artefacts of the classical methods mentioned above.

By leveraging AltaRica's compositional modeling capabilities, we aim to demonstrate a more scalable and automated pathway to safety evidence generation for small UAS certification.

2. Methodology

This study first positions AEP-83 within the broader landscape of UAS safety and airworthiness frameworks. AEP-83 is compared against the SORA (Specific Operations Risk Assessment) methodology — a risk-based operational approval framework — and STANAG 4671, which addresses airworthiness requirements for larger UAS intended to operate in non-segregated airspace. This comparative exposition highlights AEP-83's scope, its emphasis on design-level safety evidence.

We then introduce AltaRica 3.0, a model-based safety analysis (MBSA) language built around the concept of **guarded transition systems (GTS)**. A GTS models a system component

as a set of state variables, events, and guarded transitions that conditionally update those states, enabling the compositional construction of complex system models from reusable modules. This formalism allows analysts to derive standard safety artifacts — including fault trees, event sequences, and failure probability estimates — directly from a single unified model, addressing a key limitation of classical, siloed safety analysis methods.
The core of the methodology consists of a systematic, step-by-step walkthrough of the AEP-83 safety assessment process. For each major step — including the Functional Hazard Assessment (FHA), Preliminary System Safety Assessment (PSSA), and System Safety Assessment (SSA) — we evaluate how AltaRica models can be constructed, exercised, and queried to generate the required safety evidence. To ground the analysis in a concrete and tractable context, a **positioning system** (combining GNSS and inertial measurement) serves as an illustrative example throughout, demonstrating the modeling constructs and outputs relevant to each certification step.
Finally, the findings are synthesized into a **recapitulative table** mapping each AEP-83 process step to the corresponding Alta-Rica capabilities, the type of safety evidence producible, and the identified limitations or open challenges. This structured overview is intended to serve as a practical reference for safety engineers seeking to integrate MBSA tools into small UAS certification workflows.

3. Results / Conclusions

The analysis demonstrates that AltaRica can effectively perform all classical safety analysis methods required by AEP-83 — including fault trees, FMEAs, and Markov chains — within a single, unified modeling framework. Safety artifacts are derived automatically from the system model, eliminating inconsistencies between separate analyses and significantly reducing engineering effort and human error. This MBSA paradigm represents a substantial productivity gain: centralizing the system description spares analysts from manually synchronizing multiple safety documents throughout the design lifecycle, accelerating the overall certification process. When the system model is updated, all dependent analyses are regenerated consistently from a single source of truth.
Nevertheless, the Functional Hazard Assessment and system scoping decisions remain inherently expert-driven. Despite these limitations, AltaRica's modular architecture enables component reuse across UAS programs, provided that the assumptions governing each component's operational context are preserved.

Validation and Deployment Of RF and Remote ID Sensor Systems for Monitoring U-space Traffic

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1. Introduction / Objectives

The rapid growth of drone operations in urban environments has created an urgent need for robust traffic monitoring within U-space airspace frameworks. While Remote Identification (Remote ID) has become a regulatory requirement in Europe since January 2024 , ground-based sensor systems for capturing and representing drone activity remain insufficiently validated, particularly in complex urban settings where signal propagation, multipath interference, and coverage gaps present significant challenges.
This study addresses that gap by investigating the validation and operational deployment of

Senhive SEN-ID RF Remote ID sensors for drone traffic monitoring. Two structured experiments assess sensor accuracy and reliability under both controlled and urban conditions. Additionally, a real-world case study during the 2025 NATO Summit in The Hague evaluates operational applicability under active airspace restrictions. Together, these undertakings aim to advance the understanding of how current RF Remote ID infrastructure performs and where improvements are needed to enable robust U-space monitoring.

2. Methodology

This study employed a three-part methodology combining controlled experimentation, urban field testing, and operational case study analysis. The first experiment was performed at Unmanned Valley (Katwijk aan Zee, NL), a dedicated drone testing area. A Senhive SEN-ID sensor was mounted on the roof of the main facility building. Multiple drones flew standardised autonomous waypoint missions across eight predefined locations at altitudes ranging from 20 to 120 metres. Programmed trajectories were compared against recorded data to evaluate positional accuracy, detection consistency, and data segmentation behaviour. Raw data was processed via the proprietary Senhive SenAir platform and subsequently exported and converted using a custom Python workflow.

The second experiment was performed in the urban environment of the city of The Hague, NL. An off-the-shelf DJI Mini 3 Pro with integrated RF Remote ID was flown across three missions in proximity to the World Forum area, covered by two deployed SEN-ID sensors. Missions varied in environment complexity, flight speed, altitude profile, and line-of-sight conditions. Drone onboard log data was compared directly against sensor-recorded detections to assess urban detection fidelity without additional post-processing.

Lastly, a case study was performed using data from the 2025 NATO Summit in The Hague, NL. Four SEN-ID sensors distributed across the city collected drone traffic data throughout June 2025, thus including the period before, during, and after the NATO Summit. To address known limitations of the SenAir platform's flight segmentation algorithm, a custom time-based flight allocation algorithm was developed: data points belonging to the same drone were grouped into a single flight if their timestamps fell within a 120-second threshold. Geographical validation filters were also applied to exclude erroneous data points. Resulting flight counts, spatial heat maps, altitude histograms, and temporal traffic patterns were analysed to assess how imposed airspace restrictions influenced observed drone traffic behaviour.

3. Results / Conclusions

Under controlled conditions, the Senhive SEN-ID sensor reliably reconstructed drone trajectories across multiple UAS platforms, though data segmentation inconsistencies and reduced detection density at greater ranges were observed. Urban testing revealed more significant limitations: obstructions at street level prevented detection during take-off and landing phases, while unexplained transmission lapses occurred even under presumed direct line-of-sight conditions, pointing to deficiencies in the drone detection pipeline, as shown in Figure 1. The NATO Summit case study demonstrated clear operational value, with sensor networks successfully capturing traffic suppression effects corresponding to imposed airspace restrictions, and identifying individual non-compliant flights, as shown in Figure 2. Overall, RF Remote ID sensors are important for U-space monitoring, but their deployment and robust use requires improved detection algorithms, strategic sensor placement, multi-technology redundancy, and stricter regulatory compliance requirements for both drone and Remote ID beacon manufacturers.

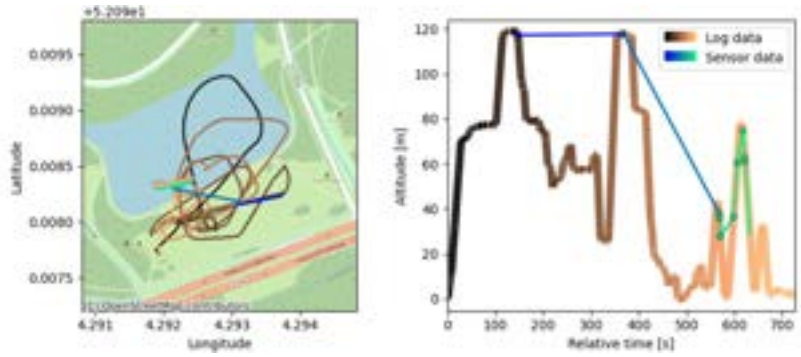


Figure 1. *Drone log data and sensor data showing detection lapses in an area with presumably sufficient sensor coverage.*

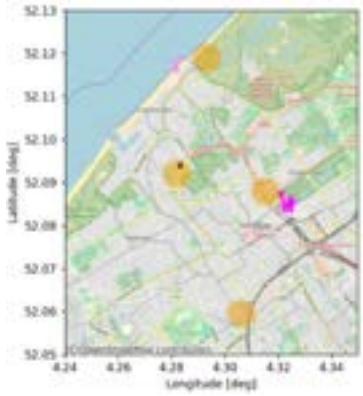


Figure 2. *Drone detections in The Hague on the 25th of June 2025, during the NATO Summit, when drone flights were restricted.*

A Microservice Architecture for UAM Fleet Control Stations in U-space Environments

Enno Nagel, Sukhbir Singh, Miguel Angel Fás Millan
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1. Introduction / Objectives

Urban Air Mobility fleet control stations have to manage many concurrent missions in dense traffic while keeping up with changing geo-zones and weather constraints.
We describe a simulation-first microservice architecture for UAM fleet operations in EU U-space.
The design keeps low-rate, auditable command interactions separate from high-rate operational facts, and it uses a versioned U-plan contract to make strategic authorisation and vertiport coordination traceable.
The explicit split between command plane and fact plane keeps supervision responsive without giving up regulatory auditability.

2. Methodology

A simulation-first fleet-control prototype is being built using the system architecture pictured below.
Regulatory requirements follow EU Regulation 2021/664 (covering network identification, geo-awareness, traffic information, flight authorisation).
Operators access the system through authenticated web interfaces, while a fleet backend handles mission planning, approval requests, monitoring, and audit logging.
Private fleet data were kept in an internal database, and only the minimum information needed for external coordination was exchanged with a single U-space Service Provider (USSP).
For each mission, the backend first retrieves current operational constraints, including geo-zones, weather, traffic information, and vertiport availability.
It then generates a time-stamped 4D route with an internal path planner and checks the route for likely conflicts before submission.
Low-rate coordination steps such as flight-authorisation requests, hold negotiation, and plan publication were sent through a REST command interface for traceability and replay after failures.
High-rate operational data such as telemetry, plan-following status, and alerts are exchanged separately through message brokers using MQTT (fleet-company) and AMQP 1.0 (UTM).
The prototype uses an ownship simulator, telemetry adapters, and synthetic traffic and environment feeds.
Both nominal and disrupted cases, including timeouts, token expiry, and late constraint changes, are used to assess workflow stability, auditability, supervision workload, and routing quality.
Validation will follow a staged plan:
simulation campaigns, human-in-the-loop trials in the DLR IAM-CC environment, and field experiments in Cochstedt, Germany.

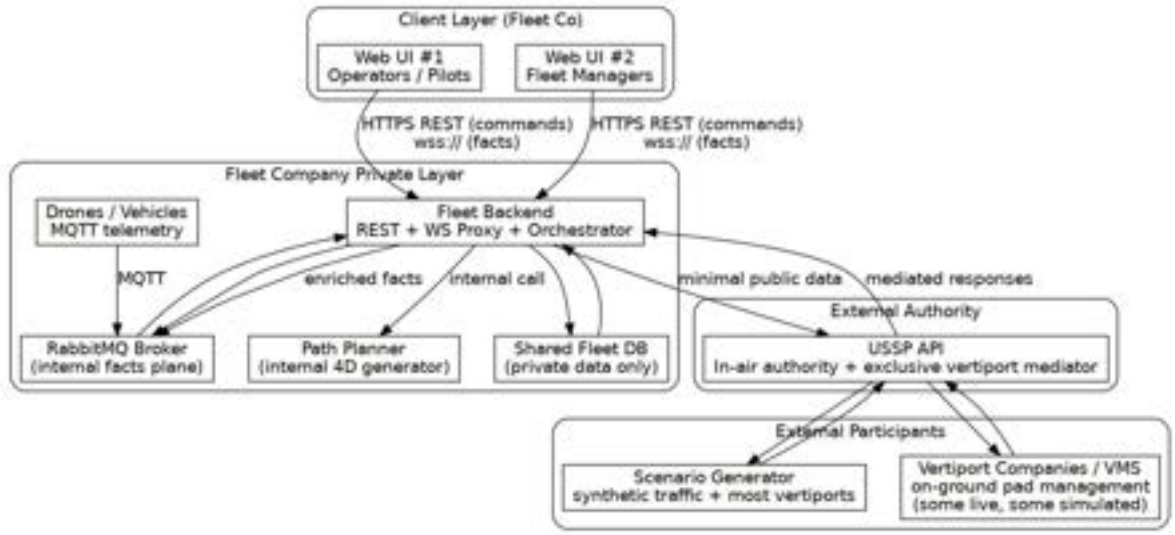


Figure 1. *This is a figure.*

3. Results / Conclusions

The prototype demonstrates principal feasibility of the proposed architecture and command/fact-plane separation.
All nominal steps (constraint retrieval, vertiport hold negotiation, strategic authorisation, publication) and representative non-nominal cases (timeout with idempotent replay, token expiry, constraint invalidation) execute with stable audit trails.
Planned human-in-the-loop campaigns will quantify supervision scalability, re-authorisation robustness under dynamic constraints, and multi-actor coordination effectiveness.

Control of Multirotor with Slung Load Using Deep Reinforcement Learning

Giulio Avanzini, Fabio Polese, Alessandro Zavoli, Guido De Matteis
Sapienza Università di Roma, Italy

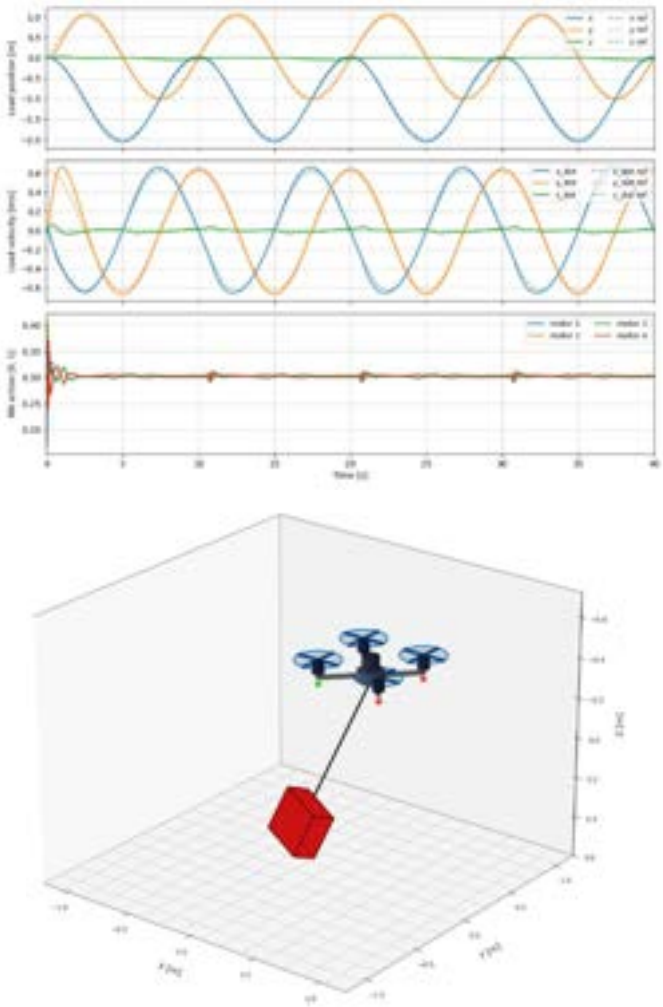
1. Introduction and Objectives

Transport of a slung load with one or more multirotor platforms presents several challenges. The tightly coupled dynamics of the vehicle with the lightly damped oscillations of the slung load make the control task extremely difficult, especially for accurate trajectory tracking. If only one multirotor is used, amplitude of load oscillations during transient maneuvers, including a simple acceleration or deceleration, may become large, possibly sparkling instabilities in the closed-loop system. When the payload is attached to two multirotors, one oscillatory degree of freedom is still present. If more than two multirotor are used for transport of the slung load, the problem shifts towards an adequate control coordination, which keeps cable tension within acceptable limits for all the formation agents. The objective of the paper is to investigate deep reinforcement learning as a tool for the control of the agents (vehicle and slung load).

2. Methodology

Each multirotor is modeled as a rigid body, controlled by means of rotor angular rates. The suspended payload is also considered as a rigid body, attached to one or more multirotor by means of inextensible massless cables. The resulting system dynamics for the multi-agent case is similar to that described in . Different cases will be considered as a test benchmark for the use of reinforcement learning for transport of a suspended payload: transport by means of a single agent (Case 1); transport by two agents in tandem and side-by-side configurations (Cases 2.a and 2.b); three agents, resulting in an isostatic system (Case 3); and a case with four or more agents, resulting in an hyperstatic over-constrained system (Case 4). The multirotor–slung load system control problem is formulated as a Markov Decision Process (MDP) and solved using Multi-Agent Proximal Policy Optimization (MAPPO) with parameter sharing . MAPPO is a multi-agent generalization of Proximal Policy Optimization (PPO) that follows the Centralized Training with Decentralized Execution (CTDE) paradigm: a shared critic observes the full global state during training (all agent and load states), while each agent acts on its local observation (single agent and load states) at execution time. To preserve individual agent identities within the shared network, each observation is augmented with an encoded agent ID. To promote robust generalization, the agent network is trained by tracking random minimum-snap trajectories . The reward function is shaped to encourage load position tracking, damp load oscillation and enforce collision avoidance among agents.

The framework is implemented using a custom Python library built on PureJax , integrated with Gymnax environments, exploiting massive GPU parallelization to simulate thousands of environments simultaneously and significantly reduce training time.



(a) (b)

Figure 1. *Tracking performance and NN action vs time (a), one agent configuration; 3D snapshot of the training (b).*

3. Results and Conclusions

Two major results will be proposed. First, it will be proven that a single well-trained neural network (NN) can handle the dynamics of the system with a suspended payload, independently of the number of agents, while damping out payload oscillations and tracking a prescribed reference trajectory for the payload. At the same time, the NN can configure the formation without the need of any external information, that is, the relative position of agents during the execution of the required maneuver is not prescribed, rather it follows a trajectory which enforces the prescribed suspended payload motion. Additionally,

this work serves as a validation benchmark for a custom JAX-based RL library develop in-house by the authors, demonstrating its effectiveness in training complex multi-agent control policies through a fully GPU-accelerated pipeline. Figure 1 shows the tracking performance of the trained NN for the single-agent case, along with a snapshot of the training process.

Neuro-Adaptive Tactical Path Planning for Fixed-Wing UAVs in Terrain- and Threat-Constrained Environments

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1. Introduction / Objectives

This study proposes a neuro-adaptive tactical path planning framework over DEM-based terrain under threat and flight-feasibility constraints. Conventional planners such as A*, RRT* etc. generate geometrically valid paths that violate fixed-wing kinematic limits. To address this gap, the proposed framework combines neural risk perception, adaptive planner selection, and fixed-wing-aware trajectory generation. The framework follows a perception-decision-action architecture. A DNN-based Tactical Risk Estimator provides fast risk estimates from terrain and threat information. A neuro-adaptive advisor computes a fused tactical index from tactical metrics and selects among RL-Pilot, K-GNP, and T-GNP planners. K-GNP introduces heading-aware graph search with turn-feasibility constraints, while T-GNP adds adaptive speed selection, time-integrated threat exposure, and tactical cost shaping.Monte Carlo simulations show that the proposed framework can generate flyable, threat-aware, and mission-suitable trajectories for flight. The work supports mission-planning technologies by integrating perception, adaptive decision-making, and aircraft-feasible path planning into a unified framework.

2. Methodology

The framework is evaluated through Monte Carlo simulations across multiple DEM-based scenarios with varying terrain complexity, threat density, mission length, and dynamic threat behavior. Performance is assessed using success rate, path length, mission time, integrated risk, tracking error, maximum bank angle, control saturation ratio, and computation time. This methodology enables a controlled comparison between classical planners, stochastic optimizers, reinforcement-learning guidance, and the proposed neuro-adaptive framework. To bridge the gap between geometric routing and physical flight reality, it establishes environment integrated with strict aerodynamic constraints used 3-DoF Aircraft Kinematic model and Terrain & Threat Modeling. The perception-decision-action architecture has real-time routing through three interconnected layers, Perception Layer (DNN-TRE), replaces traditional, Geometric Line-of-Sight (G-LOS) ray-tracing with a fully connected regression network. It maps input vectors (threat distance, relative altitude, terrain slope, threat level) to a spatial risk value via forward pass. The Decision Layer (RL Advisor), evaluates tactical scenarios using Multi-Criteria Decision Analysis. It weights three core metrics. *Capability* (threat severity), *Opportunity* (corridor safety), and *Pressure* (dynamic urgency) to compute a fused tactical risk index, adaptively choosing the best downstream planner. The Action Layer (Tactical Planners), deploys one of three custom planners based on the advisor's choice; RL-Pilot, a Dueling Double Deep Q-Network (D3QN) trained via mixed-scenario curriculum learning. It maps an 8D state vector to 5 discrete heading actions for sub-second reactive maneuvers. K-GNP, dijkstra-based search that expands a heading-augmented state

space, immediately pruning primitives that violate minimum radii. T-GnP, an extension of K-GNP for highly constrained zones that applies turn-aware cost shaping and an adaptive curvature-based target velocity policy. All generated waypoints are processed through a central Feasibility Engine (flight controller) that introduces realistic horizontal wind noise and sensor disturbances. The system benchmarks the proposed architecture against classical deterministic (A*, Dijkstra) and stochastic/swarm-based methods (RRT*, PSO) across four progressively complex scenarios S1 to S4 transitioning from open terrain to moving threat systems). Performance is cross-examined using multi-attribute metrics: success rate, tracking error, computation time, path length, mission duration, and integrated risk exposure. The aircraft model is reduced-order, 3-DoF fixed-wing point-mass representation that relies on Stevens and Beard .



Figure 1. *Neuro-Adaptive Mission Planning Architecture*

3. Results / Conclusions

The framework achieves a 100% mission success rate in Monte Carlo simulations, drastically outperforming traditional stochastic planners like RRT*, which drop to a 16.6% success rate under dynamic threats.

In the perception layer, the DNN-TRE adopts the surrogate model approach of Forrester et al. and the deep learning foundations of Goodfellow .By replacing computationally heavy physics-based geometric ray-tracing, it achieves a 3.4× speedup while maintaining a 0.9345 spatial correlation with actual risk topologies.

The action layer deploys three specialized kinodynamic planners. This includes a highly reactive, Dueling DQN-based RL-Pilot—built on the reinforcement learning architecture of Mnih which eliminates control saturation and keeps tracking errors under 21.53 meters.

Controllability Assessment of a Tiltrotor VTOL under Single Actuator Faults

Fabian Sion[1], Mark Henkenjohann[1], Udo Nolte[1], Christian Henke[1], Ansgar Trächtler[2]
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[2] Paderborn University, Germany

1. Introduction / Objectives

As Vertical Take-Off and Landing (VTOL) aircraft increasingly operate in populated environments, safety assessment has become a critical design requirement. A key metric in this context is the controllability of an aircraft, which must be maintained even under an actuator fault to comply with regulatory frameworks . To investigate the controllability of the nonlinear, constrained dynamics of VTOL aircraft, set-based approaches to compute and analyze the set of attainable forces and moments have been applied to multicopters (e.g., in) and Lift-and-Cruise VTOLs (e.g., in).
This paper extends set-based controllability methodologies to a tiltrotor VTOL with four individually tiltable propellers. The objectives are to investigate its controllability under nominal conditions and under single actuator failure during hover flight, and to identify the conditions under which the presented tiltrotor VTOL remains controllable. To ensure controllability with only three operational propellers, the tilt capabilities are exploited and optimized.

2. Methodology

The approach is based on calculations of convex sets of attainable moments in a system with admissible constrained actuator inputs . This can be applied and extended to VTOLs to calculate a set of specific forces and moments summarized as a set of attainable accelerations . As existing approaches only address VTOLs with static propellers, this paper extends these approaches to calculate a convex set of admissible inputs, the propeller forces and moments, for tiltable thrust vectors during hover flight. For the nonlinear dependencies of the tilt angles in the effectiveness matrix, a reformulation is presented to use a linear effectiveness matrix to transform the admissible input set into a 5-dimensional convex set of attainable rotational, longitudinal, and vertical accelerations, summarized as an attainable control set. For the computation of the 5-dimensional convex set, the Quickhull algorithm is used, and a dimensional reduction is applied by fixing the translational accelerations to steady hover flight conditions.
Using the same procedure, attainable sets for the VTOL with a single actuator fault, either a front or rear propeller, are calculated, compared, and analyzed. The tilt mechanism allows the exchange of the vehicle's pitch angle with the mean tilt angle of the propellers, thereby modifying the lever arms of the thrust vectors while maintaining hover thrust to compensate for gravitational force. This mechanism is used to identify the influence of the maximum tilt angle range and the optimal pitch angle to achieve controllability and maximize the attainable set with only three operational propellers, requiring no reconfiguration of the vehicle. Figure 1 shows the attainable set for the rotational accelerations, with a rear propeller fault. The trim point is on the border of the attainable set for $0°$ pitch and within the set for $45°$ pitch, making the VTOL only controllable at an inclined pitch angle.
The controllability is then validated in simulation using an INDI-controlled rigid body model containing absolute and dynamic actuator constraints, 6-DoF equations of motion, and aerodynamic models of the wings and fuselage. The model and INDI controller approach were validated for the fully functional VTOL in .

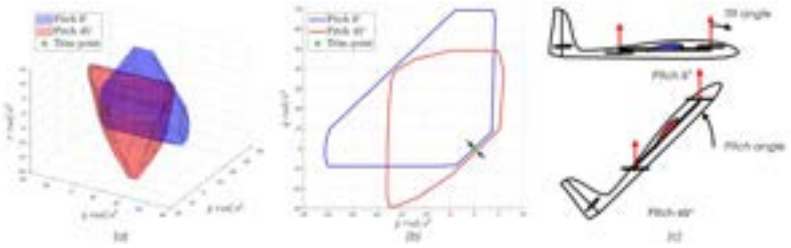


Figure 1. Attainable set of rotational accelerations
(a) 3D visualization (b) 2D visualization with $\dot{r}$ fixed at $0\ rad/s^2$ (c) corresponding aircraft attitude

3. Results / Conclusions

This paper demonstrates the capability of a tiltrotor VTOL to regain controllability during any single propeller fault in hover flight by utilizing the mean tilt angle in conjunction with an inclination of the nominal vehicle's pitch angle. Since a tilt mechanism failure would result in a propeller shutdown in the worst case, this confirms that no single actuator failure leads to a loss of controllability. Furthermore, the required tilt range and vehicle attitude are investigated to maximize controllability. These results provide the basis for expanding the controllability analysis of the attainable control set for tiltrotor VTOLs and for proving robustness against any single point of failure in the entire flight envelope. The results may also be used for the implementation of fault-tolerant control algorithms that can account for actuator faults while respecting the attainable accelerations.

Model Based System Synthesis for the preliminary design of a multirotor drone

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[2] Dassault Aviation, France

1. Introduction / Objectives

Many existing modeling frameworks can be applied to the design of aircraft systems. Among these Model Based System Engineering (MBSE) proposes modeling both the system definition and the requirements in order to evaluate these specifications by the use of analysis and simulation tools while Multidisciplinary Design Optimization) (MDO) represents the design problem as a bipartite graph between a set of variables and a set of specialists. The connections between specialists via the problem variables are established using an incidence matrix renamed XDSM , leaving it to mathematical optimization tools and/or metaheuristic-based tools to solve the problem. The objective of this paper is to demonstrate how a new approach called Model-Based System Synthesis (MBSS) can be used to represent and automatically solve a multirotor UAV optimal sizing problem that was initially modeled and solved in the literature using MDO .

2. Methodology

Several basic principles characterize the MBSS approach:

- Structured modeling of the design problem rather than the description of a candidate system.

- Simultaneous consideration of multiple heterogeneous requirements.

- The use of requirements to reduce the space of requirement-based solutions using a computational tool based on constraint programming on mixed domains. The computational method used is mathematically guaranteed. Multiple correct-by-construction design solutions can be generated with the assurance of their admissibility and their optimality.

The MBSS metamodel proposes representing a system synthesis problem as a set of requirements posted on a subdefinite model (containing degrees of freedom or unknowns) of the system to be designed. The representation of the subdefinite system clearly separates the structural and hierarchical modeling of the system from its hierarchical behavioral representations. Several types of properties can be modeled: linear or non-linear equations and inequalities, pseudo-Boolean, piecewise-defined conditional equations and catalogs. DEPS , a declarative and textual model- and property- based language for system synthesis problem is used for building models inside the DEPS Studio modeling and solving environment. In the paper we focus on formulating and solving a design problem for a multirotor drone. Such a drone is a structured, decomposable system consisting of a frame, four arms, and four power transmission chains, each comprising an electronic speed controller (ESC), an electric motor, and a propeller. A battery supplies the electrical energy required to power these four powertrains. Each component must be sized to meet a set of structural and nonlinear performance constraints so that the drone is capable of performing its assigned mission while minimizing the total mass of the system. The mechanical, electrical, and aerodynamic laws were developed by.

Two variants were proposed:

- considers a problem without off-the-shelf components. Everything must therefore be sized based on the physical laws governing each component.

- assumes that batteries and motors are selected from given off-the-shelf catalogs, with the rest of the system sized using the laws of physics.

We modeled these two variants of the problem using the MBSS approach in DEPS and solved them in DEPS Studio.

4. *Results / Conclusions*

   For a flight mission covering 2 km and carrying a payload of 250 g, the DEPS Studio solver proposes a drone with a mass of 1.03 kg. This mass is optimal because if we search for a solution with a lower mass, the solver proves that there is none. The results are consistent with actual drone design. With a battery discharge time of 406 seconds, propellers with a diameter of 12 cm, and 136 W motors running at 507 rps (approximately 30,000 rpm), these values align with those found in real-world systems. The guaranteed result is obtained in approximately 25 seconds on a personal computer with an Intel Core i7 processor clocked at 2.80 GHz and equipped with 16

GB of RAM, with an interval resolution of 1E-03.
This is an initial study aimed at applying the MBSS approach, to problems addressed within the context of MDO.

Novel Propulsion Architectures

Chaired by:
Mr. Nicolas Tantot (SAFRAN Aircraft Engines SA, France)

European aero-engine research policy from NPA Technology Cluster perspective addressing the upcoming 10th Research Framework Programme

Ralf von der Bank[1], *Nicolas Tantot[2]*
[1]Rolls-Royce Deutschland, Germany
[2]SAFRAN Aircraft Engines SA, France

1. Introduction / Objectives

This presentation introduces the "Novel Propulsion Architectures Technology Cluster" (NPA-TC), a European research network established in 2016 as sub-body to the EIMG, dedicated to the development of innovative propulsion technologies for aviation. The cluster aims to contribute to climate-neutral, competitive, safe, and affordable air mobility, and to drive the decarbonization of air transport through the advancement of technologies such as hydrogen and advanced propulsion concepts. NPA-TC brings together leading industry partners and academic institutions, supporting the research and innovation strategies of ACARE and EC.
The cluster's core objectives include reducing energy and fuel consumption, emissions, enhancing efficiency, lowering complexity and costs. Research activities span both disruptive and evolutionary technologies, covering a wide range of topics such as distributed and hybrid propulsion, novel thermal cycles, alternative fuels including hydrogen, and electrification.

2. Methodology

The presentation reviews in the field of aviation propulsion the evolution and funding of European research projects from FP5 to Horizon Europe, highlights challenges posed by stagnating budgets and the lack of continuity between medium and high technology readiness levels (TRLs), and emphasizes the necessity of continuous, long-term research. Finally, it underscores the crucial role of industry and research in maintaining Europe's competitiveness and in implementing sustainable aviation technologies.

EIMG	Engine Industry Management Group
NPA - TC	Novel Propulsion Architectures Technology Cluster
ACARE	Advisory Council for Aviation Research & Innovation

Revolutionary Propulsion: From an Idea to a Proven Concept. And Beyond?

Arne Seitz
Bauhaus Luftfahrt, Germany

1. Introduction

Advanced propulsion system technology will remain a key factor in achieving aviation's long-term climate and sustainability targets. The required step improvements in system efficiency and emission characteristics demand design solutions that go beyond the classic technological evolution. The search space for novel solutions targets ultra-high thermal and propulsive efficiencies, extremely low non-CO_2 emissions, as well as full compatibility with contrail avoidance operations. New conceptual ideas need to be identified and systematically explored regarding their long-term economic and environmental competitiveness as well as their disruptive potentials. The physical fundamentals of such novel propulsion architectural options need to be captured, and their multidisciplinary characteristics need to be appropriately modelled. Then, rigorous technical assessments need to be conducted at a very early stage, to identify suitable candidates for subsequent speedy technology maturation targeting the mid-century market demands in commercial air transport. The present contribution provides key insights from Bauhaus Luftfahrt's (BHL) low-TRL (Technology Readiness Level) activities in novel propulsion concepts conducted within collaborative research projects funded by the European Union and highlights follow-up steps required to pave the way to real impact.

2. Methodology

BHL's Innovative Propulsion Systems (IPS) group targets the development and initial evaluation of ultra-efficient and potentially disruptive concept ideas for sustainable future aero propulsion. Therefore, the team follows a basic incubator approach comprised of five key elements that aim at reaching the stage of conceptual proof (TRL 3) for highly promising, novel propulsion architectures: 1) the monitoring and assessment of technological developments with high relevance to propulsion systems; 2) the conceptual synthesis of novel propulsion and power system configurations with a good level of technical creativity; 3) the development of the required methodological capabilities in propulsion system design and performance synthesis; 4) the conduct of holistic technical concept assessments and numerical support of initial validation testing; and, 5) the derivation of recommendations and roadmaps for further research and development to support strategic decision-making. The IPS portfolio of topics developed in this manner spans across four main fields: 1) revolutionary heat engines with potential to breach the thermodynamic limits of the Joule-Brayton cycle; 2) best and balanced ways to utilise electric energy and power within aircraft propulsion systems; 3) more synergistic propulsion-airframe integration; and, 4) new propulsion system opportunities enabled by renewable alternative fuels. Major progress in the exploration and technical maturation of important conceptual candidates in all of these fields has been achieved through collaborative research projects funded by European framework programmes. Specifically, parallel hybrid electric gas turbines have been initially explored as part of integrated collaborative research (Level 2) projects during the 7th Framework Programme (FP7) such as „E-BREAK" or "ENOVAL" and later matured within the Horizon 2020 (H2020) flagship project "IMOTHEP" . The ultra-efficient Composite Cycle Engine (CCE)

concept featuring a piston-based gas generator in the core has been studied broadly for aircraft applications ranging from the regional to the long range market segments in FP7-L2 "LEMCOTEC" and H2020 "ULTIMATE" , and is currently in the focus of the Horizon Europe (HE) projects "MINIMAL" and "EXAELIA" . Advanced fuselage boundary layer ingesting propulsion integration by means of a Propulsive Fuselage Concept (PFC) has been initially studied and eventually matured to TRL3 during FP7 "DisPURSAL" and H2020 "CENTRELINE" . Innovative combinations of advanced hydrogen fuel cells and gas turbines in synergistic hybrid power systems are currently studied within the HE projects "HOPE" and "HYLENA" .

3. Results

This contribution summarises important and latest results obtained from the above-mentioned studies. This includes key design characteristics as well as the assessed potentials for improved energy efficiency and non-CO_2 emission reductions. Beyond this, cross-cutting synergies for further enhanced impact of the underlying technology concepts are discussed and next research and development steps are proposed to support possible industrial uptake. The presented findings showcase the strong value and importance of funded collaborative research in advanced propulsion at the European level.

Acknowledgement: This work has received funding from the European Union under grant agreement No. 283216, 314366, 323013, 604999, 633436, 723242, 875006, 101056863, 101096275, 101137583 and 101191922.

Challenges for integration of direct H2 combustion concepts in innovative aircraft layouts

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1. Introduction / Objectives

Achieving climate neutral aviation by 2050 requires the investigation of disruptive propulsion technologies beyond the incremental improvements of conventional aeroengines. Hydrogen-powered Turbo-Electric Propulsion Systems (TEPS), combined with innovative aircraft layouts, such as Blended Wing Body (BWB) concepts, have emerged as a promising combination considering both performance and emissions indices. However, the feasibility of hydrogen-powered TEPS remains constrained by challenges associated with components thermal management needs, cryogenic hydrogen utilization and heat dissipation under varying operating conditions. The present work is focused on the preliminary investigation of an H_2-powered TEPS powertrain implemented in a BWB layout for a MW class aircraft. The implementation is based on the integration of heat exchangers and recuperation technologies for efficient H_2 direct combustion and the use of cryocooled designs for superconducting electric machines and power electronics using H_2 as heat sink indicating that with the proper system setup significant benefit can appear.

2. Methodology

The concept is focused on the integration of high-performance thermal management components, mainly heat exchangers, tailored for H_2 fired gas turbines of MW class on a BWB aircraft platform. The investigated gas turbine is based on a core architecture similar to the one of a turboshaft aero engine which operates both as thruster and electric generator. The concept is exploiting the thermophysical properties advantages of H_2 to design advanced heat exchangers for the efficient H_2 preheating and the thermal management of the various stages of the H_2-fueled aero engine, as well as for the cryocooling of the electric motors for the turboelectric powertrain. As a result, the investigated concept, which is a combination of an aeroengine and an electric propulsion system, as shown in Figure 1 (left), provides a positive double impact: to properly preheat H_2 for direct combustion and to provide highly efficient cooling solutions for the powertrain turbomachinery and electric components.
For the analysis dedicated thermodynamic models of the aero engine were developed, as shown in Figure 1 (right), where various heat exchanger units are included, such as precooler, intercooler, turbine blade cooling heat exchanger, recuperator and secondary fluid recuperators, where the heat exchangers performance characteristics were based on the conclusions of . The aero engine concept architecture is based on the ENABLEH2 core architecture by compiling an advanced intercooled recuperated turboshaft gas turbine in its core and two bottoming cycles utilizing steam and sCO_2.

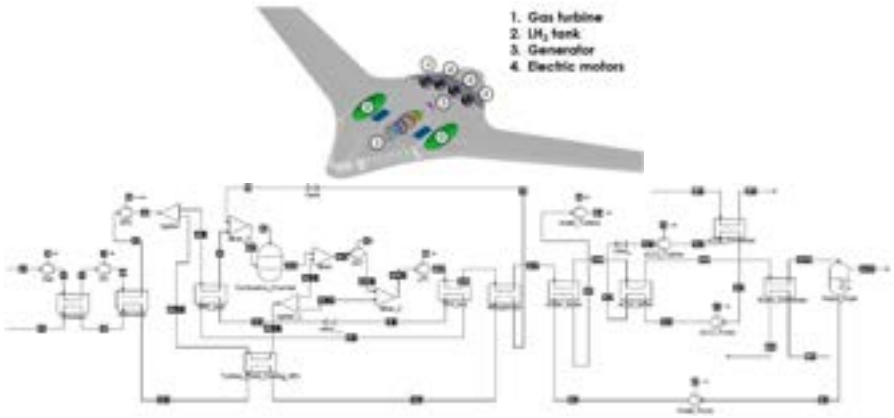


Figure 1. *Illustration of the investigated aero engine TEPS concept (left) and its thermodynamic cycle model (right).*

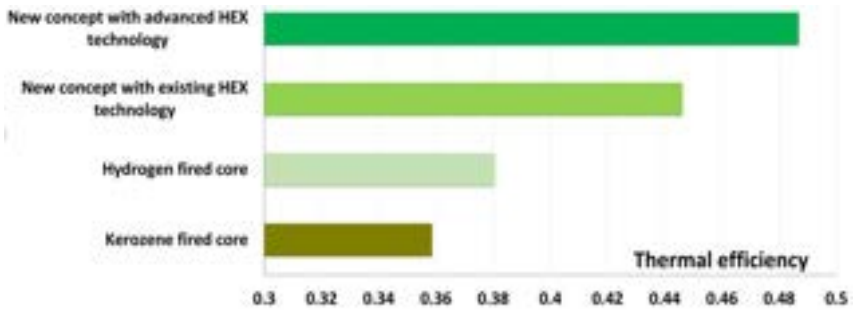


Figure 2. *Investigated core positioning vs kerosene fired gas turbines.*

3. Results / Conclusions

Preliminary level performance assessment of the investigated core architecture showed an enhanced thermal efficiency in relation to kerosene fired gas turbines, as presented in Figure 2. The analysis was performed in Gas Turb11 commercial gas turbine analysis software and COCO simulator platform for a state-of-the-art technology level 5MW class powertrain turboshaft gas turbine. As can be shown, the concept thermal efficiency increase is affected by the hydrogen heat exchangers technology level, indicating the need for more advanced hydrogen HEXs designs (higher effectiveness, reduced pressure losses, lightweight HEXs), to fully exploit the benefits of its advanced core together with the positive contributions of the Steam (H_2O) and sCO_2 bottoming cycles. As a result, the investigated concept could provide >10% net efficiency improvement in relation to a comparable kerosene fueled gas turbine of same MW class, leading to both performance increase and emissions reduction.

Ultrashort and Thin, Slotted Adaptive Nacelle for Ultra-High Bypass Ratio Turbofans.

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[2] Safran Aircraft Engines, France

1. Introduction

As the engine bypass ratio is increased for improved fuel consumption and reduced noise, the fan diameter grows, pushing the development of shorter, thinner, slim-line nacelles. By reducing the wet surface, such nacelles enable reduced weight and drag. However, they exhibit poorer aerodynamic robustness in off-design conditions, leading to fan efficiency penalties that can quickly overcome the weight and drag benefits. Indeed, as the stagnation line on the nacelle moves away from the vicinity of the highlight plane, flow turning around the inlet lip may cause separation zones that may impinge on the fan plane, leading to a loss of fan performance (Fig. 1). This paper proposes a slotted inlet concept as a means to reduce the detrimental flow features found in off-design conditions.

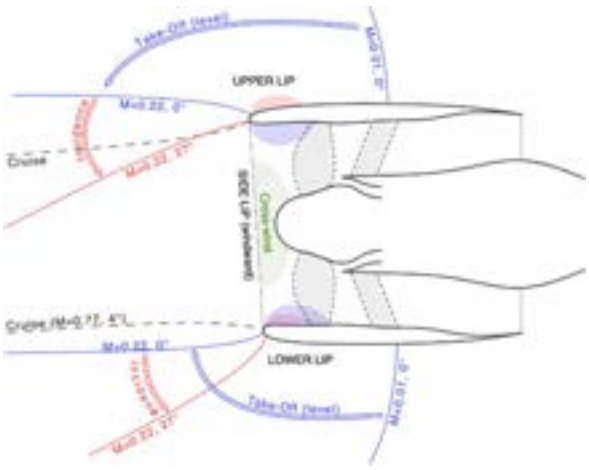


Figure 1. *Stream tube and regions prone to flow separation at different off-design conditions.*

2. Methodology

By reviewing concepts reported in the literature and comparing them to design, functional, safety, and certification requirements, we propose a translating slot adaptive-inlet concept that provides smooth lip surfaces both when extended and retracted (Fig. 2). When extended, two lips are exposed to the flow: the original inlet lip, translated upstream, and a secondary lip that forms a smooth surface with the rest of the nacelle. The non-axisymmetric converging channel between the two lips can be designed to alleviate flow separation in off-design.

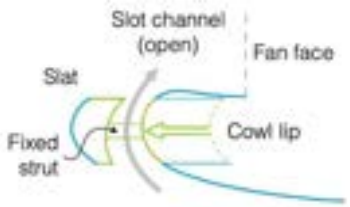


Figure 2. *Translating slot concept.*

A geometrical design framework based on Class-Shape Transformation (CST) curves was developed to create fully 3D nacelle designs, as well as the slot geometry, with a minimal number of parameters. A reference non-axisymmetric dropped nacelle design, from a relevant industrial application, was replicated using the proposed framework, and scaled down to two ultra-short designs, of length-to-diameter ratios (L/D) of 0.19 and 0.13, which are known to present flow separation ; corresponding slotted versions were then designed. For simplicity, the original and secondary lips were kept identical for both L/D designs. Integrated fan-nacelle Reynolds-Averaged Navier-Stokes (RANS) numerical simulations, based on body-force modelling (BFM) to consider the strong influence of the fan rotor on the inlet flow were performed for each nacelle design in operating conditions including cruise, take-off level and high-incidence / low mass flow climb conditions. The BFM source terms are derived from a relevant high-bypass ratio fan. Slot performance is quantified and summarized by its impact on the stagnation pressure loss coefficient and the circumferential distortion index, compared to un-slotted designs. In order to assess possible actuation scenarios, aerodynamic forces acting on the slot are estimated by integrating pressure and shear forces over the slot surface.

3. Results

The proposed slotted inlet concept simulations successfully replicate the effect of the zero-length slotted-lip inlet studied in the literature on vertical take-off and landing aircraft . The converging slot concept restores an attached flow on the lower lips of the L/D=0.19 nacelle at high incidence, although for the upper lip of the nacelle, the broader range of local incidence calls for a more elaborate geometric design. The open slot creates a wake that can be ingested by the fan, but the resulting stagnation pressure loss is weaker than the separation from closed-slot configuration. The aerodynamic forces on the slot suggest the possibility of passive deployment and retraction of the inlet slot, as the strong flow turning

around the lips, which causes the flow separation, also exerts a forward pulling force on the slot.

Development of a Hydrogen-Fuelled Opposed-Free-Piston Engine Test Rig for Characterising Performance and NOx Emissions

Joseph Harper, Andrew Rolt, Gaurav Singh, Vishal Sethi
Cranfield University, United Kingdom

1. Introduction / Objectives

Over the past two decades, a series of EU-funded projects (NEWAC, LEMCOTEC, ULTIMATE, and ENABLEH2) have explored advanced aircraft propulsion concepts targeting step-change improvements in thermal and propulsive efficiency, as well as reductions in CO_2 and non-CO_2 emissions. These improvements can be enabled through novel combustor technologies and the synergistic integration of multiple propulsion technologies. Composite Cycle Engines (CCEs) combining a gas turbine core, turbocharged piston engine topping cycles, and intercooling are predicted to deliver double-digit reductions in fuel burn . The use of hydrogen as a fuel for such engines offers further advantages through the elimination of direct CO_2 emissions, although mitigation of NOx emissions remains a key challenge due to the high stoichiometric flame temperature of hydrogen. This work describes the development of a hydrogen-fuelled Opposed-Free-Piston (OFP) experimental rig at Cranfield University as part of the ongoing MINIMAL project, with the primary aim of achieving high thermal efficiencies and low-NOx combustion.

2. Methodology

The proposed CCE concept, shown in Figure 1, integrates multiple piston engine topping cycles within a turbofan engine, exploiting the higher peak pressures and temperatures generated in the cylinders to enable pressure-rise combustion. In doing so, engine core thermal efficiencies can be markedly increased, breaching the practical efficiency constraints of gas turbine engines. The engine is intended for use in short range aircraft, fuelled by hydrogen. OFP engines are attractive options for this concept, as they offer the advantages of variable compression ratio capabilities and produce low vibration due to symmetrical piston motion. Additionally, the considered OFP engine design incorporates electrical power generation, whereby permanent magnets embedded within the opposed pistons generate electricity through electromagnetic induction as they pass through solenoid coils located at either end of the engine.

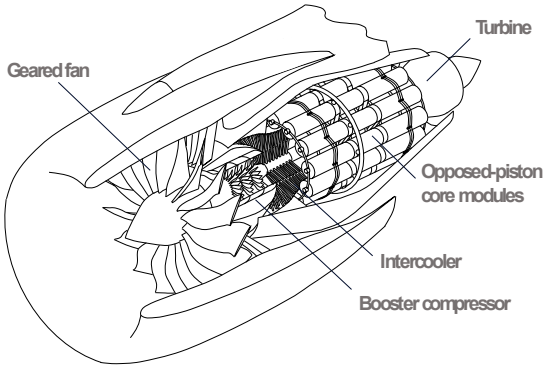


Figure 1. *Proposed Composite Cycle Engine with Opposed-Free-Piston topping modules and intercooling*

The feasibility of OFP engines for CCE applications is being investigated using a single-cylinder, hydrogen-fuelled, two-stroke OFP engine rig, procured from Libertine FPE and located at Cranfield University. To minimise NOx emissions, the engine targets highly premixed lean combustion through early direct injection, enhanced by the naturally high diffusivity of hydrogen, thereby reducing flame temperatures and preventing hot spots in the cylinder . The effectiveness of in-cylinder fuel–air mixing under the proposed operating conditions has been investigated using a high-fidelity CFD model incorporating moving mesh techniques to represent piston motion. The engine is initially configured for Spark Ignition (SI) operation, although a transition to Compression Ignition (CI) operation using high compression ratios and boost pressures is planned to maximise thermal efficiency. This transition is intended to be achieved through spark-assisted CI, leveraging the engine's variable compression ratio capability. Thermodynamic performance modelling has also been used ahead of experimental activities to generate initial P–V diagrams and simulate piston motion.



Figure 2. *The Opposed-Free-Piston engine rig in its containerised test cell*

For experimental testing, a custom-built containerised test cell (Figure 2) has been designed and constructed with rigorous hydrogen safety provisions. A combination of passive fuel-line restrictions and active ventilation systems has been implemented to prevent the accumulation of flammable hydrogen–air mixtures under full-leak scenarios. CFD modelling of multiple leak cases has been performed to validate the installed ventilation strategy. Additional safety measures include a remote-control room, flame detector camera, multiple hydrogen detectors, and a blowout panel. NOx emissions will be collected using a Signal

MaxSYS900 gas analyser, while extensive instrumentation installed within the engine provides multi-location pressure, temperature.

3. Results / Conclusions

The work undertaken represents a key step towards experimentally demonstrating the feasibility of hydrogen-fuelled Opposed Free Piston (OFP) engine as topping cycle candidates for Composite Cycle Engine (CCE) applications. An experimental OFP engine rig has been installed at Cranfield University, targeting high-efficiency, low-emission operation with hydrogen via highly premixed lean combustion and CI strategies. To support experimental validation, a dedicated containerised hydrogen test facility has been successfully developed, incorporating multiple layers of general and hydrogen-specific safety features. The experimental activities are supported by preceding modelling activities, including reduced-order thermodynamic performance modelling and high-fidelity CFD simulations for predicting engine operating behaviour, in-cylinder mixing, and NOx emissions. The resulting experimental and modelling outputs are expected to provide a unique dataset for the analysis and simulation of CCE systems, including assessment of engine operation under representative altitude conditions.

Acknowledgement: Funded by the European Union's Horizon Europe research and innovation programme (Grant Agreement 101056863 – MINIMAL). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. Cranfield University is being funded in MINIMAL by UKRI (Innovate UK) under the Horizon Europe Guarantee. Project No. 10040930.

Reduced Order Thermodynamic Modeling of an Opposed-Free Piston Engine for a Composite Cycle Gas Turbine Aero Engine

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Cranfield University, United Kingdom

1. Introduction / Objectives

Conventional gas turbine engines are approaching their practical efficiency limits due to constraints associated with core component sizing and airframe integration, motivating the exploration of alternative thermodynamic cycles. Pressure-rise combustion concepts, such as incorporation of piston engine topping cycles, offer significant potential for improving engine efficiencies. The integration of alternative fuels such as hydrogen within these concepts also allows for zero aircraft mission-level carbon emissions. However, both pressure-rise combustion and hydrogen utilisation present significant challenges, including the potential for high NO_x emissions. This study investigates Opposed Free Piston (OFP) engines as candidates for piston topping cycles through the development of a mathematical and numerical modelling framework incorporating test-rig geometry and state-of-the-art correlations from the literature. The work contributes to next-generation propulsion research

by providing a methodology for the analysis and optimisation of piston topping cycle configurations. Future work will focus on validation against experimental test-rig data.

2. Methodology

This study comprises the development of a thermodynamic model of the OFP engine using standard equations available in the literature . A mathematical model was implemented in the MATLAB environment, with the overall methodology summarised in Figure 1. Since the engine operates at relatively low-speed conditions, leakage around the pistons (blowby) was included in the model using the approach proposed by Rakopoulos , which accounts for air trapped within the piston ring pack and gas leakage toward the nearest ports. Heat transfer was modelled using the Woschni correlation with modifications introduced by Cheng .

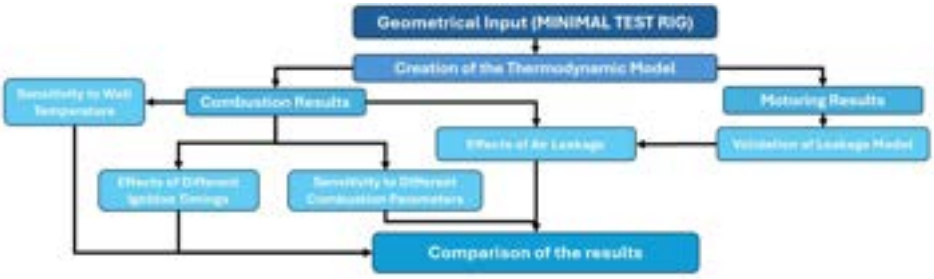


Figure 1. *Overview of the methodological framework employed in the study.*

To accurately capture hydrogen combustion effects, a modified Wiebe function based on the work of Osetrov was implemented. The function, originally validated against multiple reference piston engines, accounts for equivalence ratio, injection type, and engine speed. Gas properties were calculated using the polynomials presented in , while scavenging was modelled using the experimental correlation proposed by Pipitone . The effects of wall temperature, equivalence ratio, Wiebe function constants, and spark timing were investigated to quantify their influence on engine performance. Different operating and modelling parameters were then compared to evaluate their impact on overall component behaviour.

3. Results / Conclusions

Cycle No.	Considered Effects					
	Blow-by	Start of Combustion	Equivalence Ratio	Wall Temperature [k]	m parameter [-]	Frequency [Hz]
1	YES	10° bTDC	0.45	500	m=2	13.63
2	NO	10° bTDC	0.45	500	m=2	13.63
3	YES	10° bTDC	0.45	500	m_1=2, m_2=1.2	13.63
4	YES	10° bTDC	0.45	500	m_1=2, m_2=5	13.63
5	YES	10° bTDC	0.39	500	m=2	13.63

6	YES	10° bTDC	0.45	Adiabatic	m=2	13.63
7	YES	10° bTDC	0.45	350	m=2	13.63
8	YES	20° bTDC	0.45	500	m=2	13.63
9	YES	0° bTDC	0.45	500	m=2	13.63
10	YES	10° bTDC	0.45	500	m=2	27.26
11	YES	10° bTDC	0.45	500	m=2	6.82

Eleven simulation cases were investigated to evaluate the effects of engine speed, wall heat transfer, combustion *m* parameter, and spark timing, as summarised in Table 1, with Case 1 presented as the reference case in Figure 2.

Table 1. *Summary of different analysed cases.*
(bTDC – bottom Top Dead Centre, m, m_1, m_2 - Wiebe function combustion characteristic exponents)

The results showed that wall heat treatment and blowby leakage had the greatest influence on predicted engine performance. By modelling the engine as adiabatic and neglecting blowby, an overprediction of performance was modelled due to reduced heat losses and leakage effects. Lower modelled engine speeds increased blowby due to longer residence times, while higher speeds reduced scavenging efficiency from 95% to 67%, increasing H_2O dilution from 1.4% to 4% by volume. Based on the experimental results of Liu , this dilution level is expected to have only a minor influence on laminar flame speed. Overall, the study highlights the importance of combustion modelling assumptions and the need for further validation using experimental test-rig data to accurately predict topping-cycle performance and combustion behaviour.

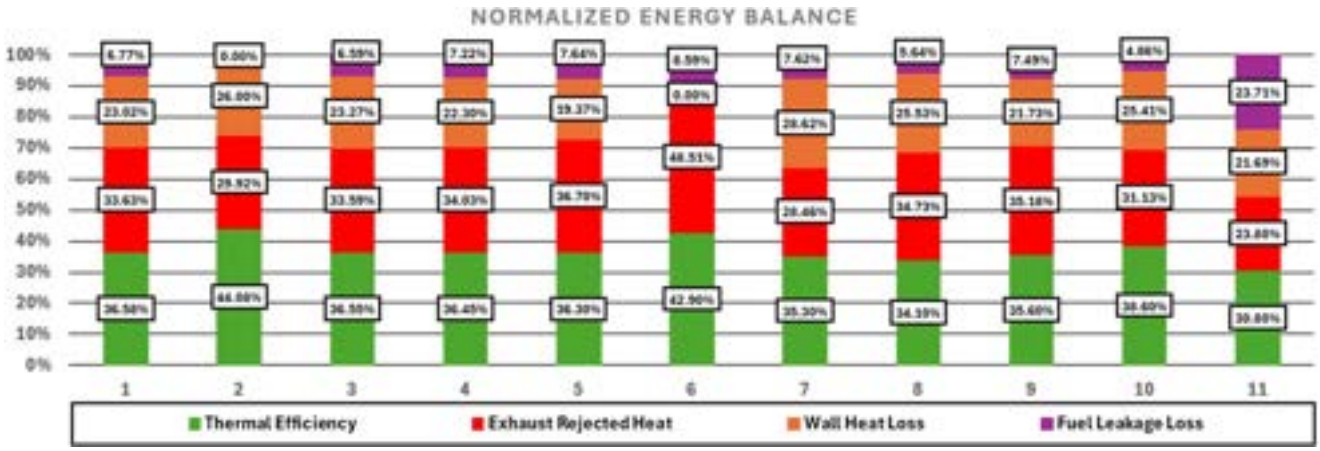


Figure 2. *Summary of different case settings and their effect on normalized energy balance.*

Acknowledgement: Funded by the European Union's Horizon Europe research and innovation programme (Grant Agreements 101056863 – MINIMAL, 101191922 – EXAELIA). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. Cranfield University is being funded in MINIMAL by UKRI (Innovate UK) under the Horizon Europe Guarantee. Project No. 10040930.

Thermal Management in Emerging Propulsion Architectures: Opportunities and Design Challenges

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1. Introduction

Most civil and military aircraft are propelled by turbofans, whose designs were improved only incrementally during the last half century. The civil aviation sector is subject to climate targets, which may require the introduction of revolutionary engine technology. This has been the backbone of several EU projects related to aircraft propulsion in the last two decades. Most of these new technologies radically increase requirement to transfer large amounts of heat via heat-exchangers, see Figure 1. Contrary to land applications, "flying" heat exchangers will benefit from a more compact and less intrusive design. This leads to challenging configurations that require short diffuser ducts coupled with flow turning that are more prone to flow separation and increase in pressure losses. Finding a good compromise between integration and performance has been the focus of several ongoing and earlier attempts. The current presentation will discuss opportunities and challenges of thermal management in emerging propulsion systems, with focus on the design and integration of large heat-exchanger on aircraft.

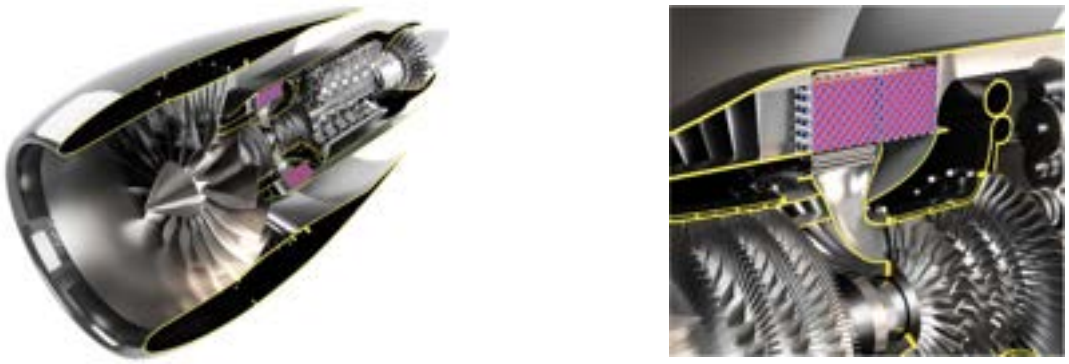


Figure 1. *The MINIMAL composite cycle engine concept relies on MW class heat-exchangers. Left: Crankshaft based Intercooled-CCE. Right: detailed view of the intercooler that relies on bypass-air and hydrogen to cool the intermediate compressed air.*

2. Methodology

At Chalmers we are developing a structured design framework for HEX design and integration in aircraft propulsion systems. The framework relies on an integrated set of numerical, analytical, and experimental approaches. Reduced-order methods such as the GenHEX framework, which represents heat exchangers using generalized parameters have recently been developed and applied for HEX matrix design activities . GenHEX allows for fast performance estimation during early design stages without specifying detailed geometry and can be fully integrated into system level models or CFD tools .Chalmers also employs multiphysics CFD simulations, including conjugate heat transfer, to capture coupled fluid–thermal behavior in advanced systems such as hydrogen-fueled engines . Finally,

experimental test rigs are used to validate simulations and improve model accuracy . A key issue is that HEX integration has remained very much case-specific and ad-hoc oriented. There is lack of a structured design approach, which typically makes HEX integration time-consuming and often leads to suboptimal configurations. Despite decades of research, there is still no widely accepted methodology that allows engineers to confidently integrate HEX into propulsion systems without relying on case studies. Chalmers is currently investigating new integration strategies and technologies that directly exploit the benefits of a coupled heat-exchanger diffuser design method .

3. Conclusions

The design and integration of MW class heat-exchangers is an enabler for future advanced propulsion systems, ranging from fully electric to hybrid electric, fuel cell, and thermal engines. Still, there is a noticeable lack of established design practices and methodologies for integrating large heat exchangers in aviation. This gap is particularly critical for future engine concepts, where efficient thermal management is essential turnkey technology. The absence of best practices is evident in several EU and Swedish research projects, where unexpected design challenges have led to ad-hoc and suboptimal configurations. Integration is identified as one of the challenging tasks, but no ready-to-use solution or design approach exists. This presentation will address the needs, the opportunities and the design and integration challenges, providing a relevant roadmap for technology development in the European aviation sector.

Hydrogen & Energy Storage

Chaired by:
Prof. Andreas Strohmayer (University of Stuttgart, Germany)

Configuration for Optimal Integration of Hydrogen Fuel for a Medium-Range Airplane

Vishwanath Nagaraj, Roelof Vos
TU Delft, Netherlands

1. Introduction

The aviation industry's transition to carbon-free fuels is a critical component of meeting global climate objectives. Despite its drawbacks of low volumetric energy density and cryogenic storage requirements, liquid hydrogen (LH2) is emerging as a promising candidate . While LH2 aircraft configurations have been examined in literature , there is little consensus on what solution is optimal; due to the lack of a direct, comprehensive comparison. This study investigates the question of which aircraft configuration is best suited for hydrogen fuel integration, in the medium-range category. Additionally, the effect of applying operational limits to the design of LH2 aircraft is examined, and compared alongside the configurations. A conceptual design framework is used to size the aircraft and quantify their performance,

while qualitative aspects of the designs are critically analyzed, including airport compatibility and safety.

2. Methodology

A concept downselection process leads to four configurations chosen for the study: 1) the conventional aft-tail, aft-tank aircraft, 2) the three-surface, aft-tank aircraft, 3) the top-tank aircraft, and 4) the forward-and-aft tank aircraft. Given its popularity in literature, the first configuration is considered a baseline, and several factors are identified that degrade the design's performance. The tank's aft placement produces a wide center-of-gravity (CG) range, resulting in a large horizontal tail, which increases zero-lift drag. The substantial in-flight CG excursion also leads to high trim drag over the mission. Additionally, the extreme aft position of the CG requires a main landing gear position that is incompatible with conventional under-wing-folding, necessitating alternative, high-drag solutions. Each of the other configurations are conceptualized to mitigate these effects and improve aircraft performance.

The Initiator is a digital framework for aircraft design and sizing, developed at TU Delft. In the current study, it is modified to be configuration-agnostic, within the limits of the study, to effectively design and analyze the aforementioned aircraft configurations. The resulting converged aircraft designs are shown in ***Figure 1***. The tool's ability to perform a time-marching mission analysis is seen as especially useful for LH2 aircraft, as it allows the effects of CG-excursion on drag to be captured. Furthermore, a semi-empirical tail-sizing module and numerical models for weight estimation demonstrate the Initiator's usefulness in designing unconventional configurations. The reference aircraft is selected as the Airbus A320neo, and its top-level aircraft requirements (TLARs) are used as inputs for sizing all configurations-maintaining a level base for the comparison. Each configuration is optimized for minimum block fuel consumption to present the best of each design philosophy. The aft-tank aircraft, designed with operational limits, ignores the ferry mission requirement when sizing the tail and positioning the landing gear. This necessitates the use of ballast for certain off-design missions but is intended to enable improved performance in on-design missions.

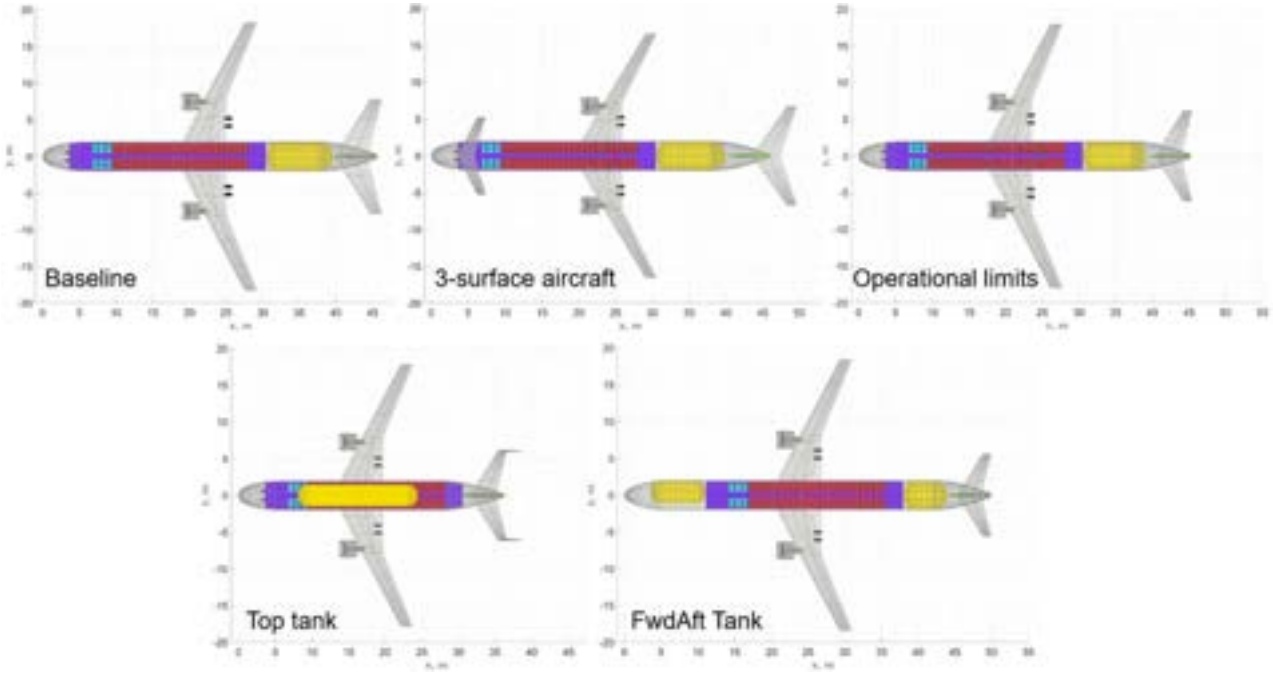


Figure 1. *The LH2 aircraft configurations designed in the Initiator.*

3. Conclusions

Compared to the baseline aircraft, the top tank configuration resolves the large CG range by placing the tank above the fuselage in a non-integral manner. This trades an increase in form drag for sizable reductions in MTOM and OEM- producing a net reduction of 2.4% block fuel consumption. The three-surface configuration and the dual tank configuration similarly trade between weight and drag, but with little to no improvement in fuel consumption. Unexpectedly, the aircraft designed with operational limits shows the most reduction in block fuel consumption at -6% compared to the baseline. It also enables conventional landing gear integration and better airport compatibility, albeit at the expense of reduced operational flexibility. Ultimately, this design alongside the top tank configuration is presented as the optimal integration of hydrogen fuel in the medium-range category; with the choice between the two being driven by market-specific requirements.

Assessment of Regional to Long-Range LH_2-Powered Aircraft with Conformal Wing Tanks

Marc Engelmann, Chang Xu, Nils Roth, Barlas Türkyilmaz
Bauhaus Luftfahrt e.V., Germany

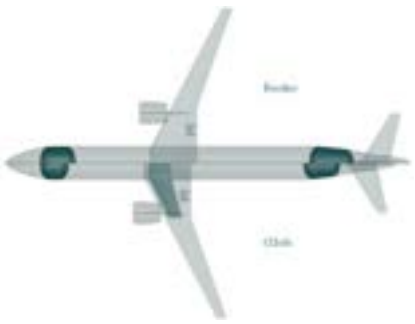
1. Introduction / Objectives

Liquid hydrogen (LH_2) powered aircraft are a potential solution for a reduced climate impact of aviation . In research consensus, the LH_2 tanks are placed within the fuselage due to given LH_2 tank design boundary conditions . The wing structure does not include any tanks.
In the CHoSe project, funded under the German LuFo program, the potential of LH_2 tanks within the wings is assessed, taking some of the required LH_2 out of the fuselage, thereby

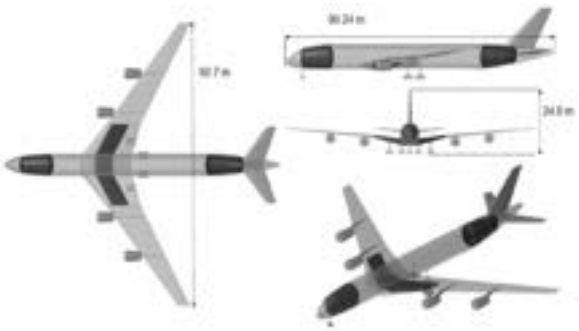
reducing the fuselage length and potentially resulting in a lower block fuel consumption. In an initial project publication by Roth et al. , the impact of the integration of these tanks into an A320-class aircraft has been demonstrated, with the reduction in block fuel mass being relatively minor. In this paper, the wing integrated LH_2 tanks are assessed for ATR72- and Airbus A380-class aircraft, exploring the concept for alternative, potentially more beneficial design spaces.

2. Methodology

This paper builds upon the modelling foundations presented in . The modelling and assessment of the aircraft is performed on conceptual design level, using the Bauhaus Luftfahrt Aircraft Design Environment (BLADE) . The initial step of the methodology is the derivation of the calibrated reference aircraft in BLADE for the ATR72 and Airbus A380. Next, the aircraft are sized with technology assumptions for the year 2035 based on. Both aircraft are transitioned to an LH_2 combusting version with fuselage LH_2 tanks only, representing the hydrogen baseline aircraft. The ATR72 configuration possesses two LH_2 tanks aft of the cabin, whereas the A380 has one tank in front of and one tank aft of the cabin. Lastly, the study aircraft are derived. They include additional conformal LH_2 tanks in the wings. For the ATR72, the available wing volume is comparably small, while the A380 has a significant available volume within, thus featuring a larger amount of storable LH_2 in the wing. Both aircraft are then sized in the aircraft design loop, while maintaining all TLARs and design specifications of the hydrogen baseline. The fuselage and LH_2 tank design logic within the fuselage is based on . The wings are filled with conformal LH_2 tanks up to a sensible spanwise location, with the rest of the LH_2 needed for the design mission being distributed inside the fuselage tanks.
A comparison of a hydrogen baseline aircraft with LH_2 tanks in the fuselage to an aircraft with additional wing tanks can be seen in Figure 1 (left) and represents the key geometric difference between the hydrogen baseline and concept aircraft assessed in this paper. On the right, the concept aircraft for the A380-class is presented.



A320 LH_2 baseline and CHoSe concept aircraft top view comparison.



A380 LH_2 CHoSe concept aircraft depiction with conformal wing tanks and fuselage integrated front and aft cabin tanks.

Figure 1. *Left: Comparison for an A320-class aircraft with fuselage integrated LH_2 tanks (top) and additional conformal wing LH_2 tanks (bottom). Right: Airbus A380-class LH_2 concept with tank front and aft of the cabin and inside the wings.*

Due to the selected conformal wing-tank integration concept, fuel-mass inertial relief acting on the wing differs from that of conventional kerosene-fueled aircraft. Therefore, the mid-fidelity aero-structural tool NeoCASS (Next Generation Conceptual Aero-Structural Sizing) and

its optimization framework are used to evaluate potential weight penalties caused by the absence of wing fuel providing bending-moment relief.

3. Results / Conclusions

The hydrogen baseline and concept aircraft are compared regarding their block fuel mass on the design and typical missions, demonstrating the impact of the utilization of unused space inside the wings for different missions. As the wing tank design is a key design choice, a parameter study is performed to evaluate the impact of the conformal wing tank design regarding structural mass and utilizable wing volume. Preliminary A380 results show a 13.2t LH_2 storage capability within the wings, highlighting the potential reduction in fuselage tank sizes. Secondarily, the ATR72, A380 and the A320 are transformed to use LH_2 wing tanks only, evaluating the possible operating space of a retro-fit where the fuselage remains unchanged compared to kerosene aircraft.
Lastly, the results of the mid-fidelity aero-structural wing optimization analysis shows that the absence of fuel-mass inertial relief results in a total wing mass penalty of approximately 5% for both A320-class aircraft and A380-class aircraft.

Acknowledgement: The project on which this paper based was funded by the German Federal Ministry of Finance for Economic Affairs and Climate Protection under the funding code 20E2204B. Responsibility for the content of this publication lies with the author.

Design Criteria Definition of Liquid Hydrogen Fuel Systems for Aircraft Application

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1. Introduction / Objectives

The conceptual design of hydrogen-fueled aircraft has gained significant attention over the past decade as a promising alternative to mitigate aviation's impact on net emissions. However, their commercialization hinges on regulatory frameworks capable of certifying this novel technology. Current certification standards must be adapted to incorporate hydrogen-specific fuel system considerations , thereby enabling the establishment of clear design requirements. Consequently, defining robust design and sizing criteria is essential for informed technology selection. While the majority of studies focuses on the hydrogen storage , other critical sub-systems, including pressurization and venting, gained less attention within the aviation research community. This study addresses this gap by establishing some design criteria for these sub-systems of a pump-driven fuel system. It identifies key operating and worst-case conditions while seeking to align with current regulatory requirements.

2. Methodology

The design criteria for the different fuel sub-systems must align with aircraft-level design requirements and regulatory standards. To systematically integrate these inputs, the methodology illustrated in Figure 1 is applied. Aircraft design requirements are first analyzed to extract baseline operational points, which are then compared alongside additional points derived from evaluation of possible worst-case operational conditions. Simultaneously,

system-level requirements are established from EASA certification standards and technical guidelines for hydrogen systems design . These inputs are integrated with the operational points previously identified to define clear and consistent design criteria. The resulting framework guides the selection of the system architecture and final sizing, ensuring alignment with certification and industrial standards.

3. Results / Conclusions

For the design criteria definition of the different sub-systems regulations and aircraft design criteria were reviewed while worst-case scenarios were evaluated. Preliminary results indicate the following operations points to be critical for the different sub-systems, the fuel flow requirement for the distribution system, critical transient events like post-takeoff and sloshing that cause significant tank pressure drop for pressurization system, insulation failure of tank and pipelines for venting system, as well as the turnaround time for refueling and defueling systems. The proper fuel system functioning under all those conditions shall be ensure by the system design to fulfill EASA requirements. The design is also guided by technical recommendations, such as pipeline design processes and maximal hydrogen erosion velocity , given by industrial standards. Finally, design criteria for the sub-systems were defined to guarantee safety and reliability across all operating envelopes. Strategic redundancy in the system architecture can avoid the need for oversized components.

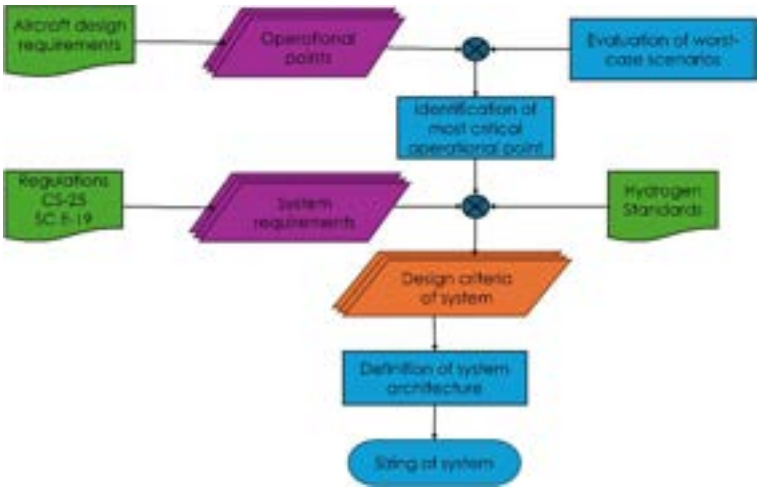


Figure 1. *Process of design criteria definition*

Hydrogen strut braced wing aircraft a common ONERA / DLR evaluation and benchmark model

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1. Introduction

In the scope of the Clean Aviation / SMR ACAP project, DLR and ONERA were tasked to evaluate several hydrogen fueled aircraft, each with one of the following conceptual changes: advanced strut-braced wing aircraft , high aspect ratio cantilevered wings and Unducted Single Fan engine. As each institute worked separately on the modelling and the integration of these new concepts, the need of a common unconventional configuration emerged to be able to better understand and put in perspective the results and the different design choices of each institution.

In this context, a new common configuration was established, modelled and studied by the two institutes. It consists of a short to medium range aircraft, fueled with liquid hydrogen and equipped with a strut braced wing and Ultra-High Bypass Ratio engines. This exercise allows the comparison of the design processes of each team based not on a reference aircraft (known aircraft) but on an unconventional configuration, for which new physical models and innovative design choices need to be taken for a study at preliminary design level.



***Figure 1**: Small and medium range transport aircraft jointly studied by ONERA (left image) and DLR (right image).*

2. Methodology

Comparing two independent studies of the same conceptual aircraft is often problematic due to inhomogeneity in the design hypotheses. For the design of hydrogen aircraft, a typical example are different requirements for the sizing of the liquid hydrogen tank leading to a large spread of the results observed in the literature . Thanks to the collaboration of the partners within the SMR ACAP project, the high-level design requirements and the design hypotheses were aligned upfront, avoiding the inhomogeneity at the input of the design processes. The differences we observe in the aircraft performances are the results of the different modelling approaches and design choices that were made during the integration in the design process. Consequently, we ambition to present both the aircraft performance results comparison and the different levels of physics representation adopted by each team. We look at what impact the choices of methods have on the aircraft design and performance predictions, but also how they guided the design choices of the two teams to achieve the best performances within the limitations of each methodological framework.

3. Results

We specifically present the following different design choices:

- LH2 tank design: advanced double conical tanks vs cylindrical and conical tank, severely impacts the rear fuselage shape, mass and drag resulting in non-negligible impacts on global performances.
- Lifting versus non-lifting strut, at high speed and at low speed, what implications on the global design.

As well as the common physical assessment:

- What makes laminarity possible for this aircraft and how much advantage does it bring.
- Strut positioning or sweep angle with respect to the wing, impact on aerodynamics and structure.

This comprehensive cross-check by two teams on a similar configuration also brings valuable information on the level of uncertainty at conceptual design level and brings confidence and robustness for future LH2 aircraft architecture definition.

Results of the *PRECISE* Project: Liquid hydrogen fuel quantity indication systems for future aircraft.

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1. Introduction

The safe and accurate measurement of liquid hydrogen (LH_2) tank fill levels is a critical enabling technology for the adoption of hydrogen as a sustainable aviation fuel, facilitating zero-carbon-emission flight. While LH_2 has been used successfully in industrial applications, as well as in road, rail, and space transportation , utilizing it in commercial aviation is especially

challenging, as the requirements for modern aircraft Fuel Quantity Indication Systems (FQIS) are significantly more demanding.
Project PRECISE is a joint venture between the Hamburg University of Applied Sciences and AUTOFLUG GmbH, aimed at the development and testing of gauging instrumentation for future LH_2-powered aircraft. The project (2023–2026) involved an extensive assessment of FQIS sensor technologies, including literature reviews, LH_2 sloshing simulations, custom sensor design, cryogenic testing, and the formulation of aircraft-level integration concepts.

2. Methodology

To derive requirements for an aviation-grade LH_2-FQIS, established automotive LH_2 standards were used, as certification frameworks for aviation-grade systems are still under development and not yet formally ratified . Specific boundary conditions, such as tank geometries and operating conditions, were adapted from extensive studies like FlyZero and EXACT .
Furthermore, the implications of LH_2 sloshing and its effects on internal sensory systems were evaluated through comprehensive CFD analysis.
A comprehensive literature review of liquid hydrogen sensors identified various mass gauging methods, which were evaluated against the boundary conditions . Consequently, promising methods were experimentally investigated by designing and fabricating lab prototypes, specifically an RTD sensor rake, capacitive probes, and optical fill-level sensors. Additionally, experiments with novel non-invasive sensing methods were conducted, such as a vibro-acoustic modal gauge and an electric fringing field sensor.
To assess the performance and durability of these prototypes, cryogenic tests were performed using liquid nitrogen as a surrogate for LH_2. Ultimately, a heuristic optimization algorithm was developed to determine optimal sensor positions within a reference liquid hydrogen tank adapted from Kotzem et al. , and the full FQIS was modeled within a graphical programming environment to investigate critical operating scenarios.

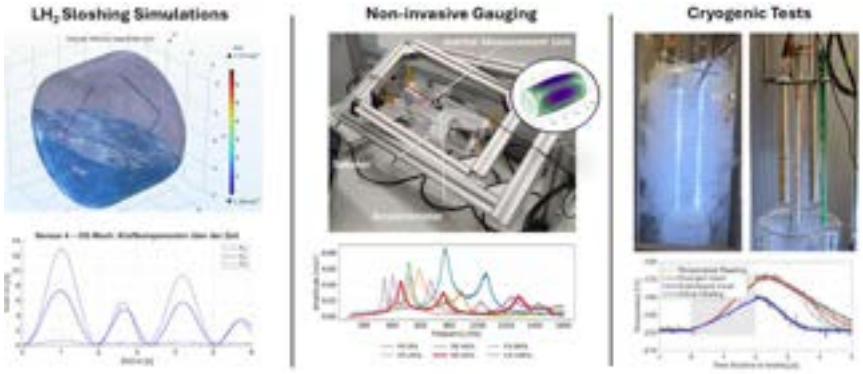


Figure 1. *left: LH_2-sloshing simulation in COMSOL Multiphysics,*

middle: vibro-acoustic-modal gauge prototype,

right: cryo-testbed

3. Results / Conclusions

Within the PRECISE project, promising LH_2 fuel gauging sensors were identified and tested. It was demonstrated that traditional capacitive probes perform well in liquid nitrogen, and it is projected that they can achieve accuracies sufficient to meet requirements. Furthermore,

RTDs were demonstrated to work reliably as discrete fill-level sensors for redundant high- and low-level detection. Initial simulations and experiments with a non-invasive vibro-acoustic modal gauge validated the feasibility of this measurement principle; however, further testing is required to confirm its suitability for large LH_2 fuel tanks. Additionally, the developed models and optimization algorithms allow for flexible adjustments to be utilized in specific aircraft FQIS developments.
This project provided an essential advancement in the FQIS specifications needed to enable LH_2 aviation.
The authors would like to thank colleagues from various research institutes and industry for their valuable and engaging discussions regarding the challenges of LH_2 gauging. This research was funded by the Federal Ministry for Economic Affairs and Energy.

Optimised Dished-End Profiles for Lightweight LH2 Tanks: An Analytical-FEA Framework

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1. Introduction / Objectives

Liquid hydrogen tanks for aerospace applications must achieve high gravimetric efficiency, making structural mass a critical design parameter. Standardised dished-end geometries (hemispherical, ellipsoidal, and torispherical) were established for producibility rather than structural optimality and inherently produce stress concentrations at the knuckle region that require conservative wall thicknesses . Traditional cold-forming and spinning manufacturing further constrain any geometry departure from these standards. Wire-arc directed energy deposition (waDED) additive manufacturing removes these constraints, enabling continuously variable meridional profiles. Within the AUTARK project (FFG No. 5138855) targeting lightweight LH_2 tank systems in light metal alloys, this work presents an automated optimisation framework coupling analytical shell-theory models with axisymmetric finite element analysis (FEA) to generate structurally improved, additively manufacturable dished-end geometries.

2. Methodology

Head geometry is parameterised using Bézier curves, with constraints enforcing tangency to the cylindrical shell and non-negative meridional curvature. Drawing on Sowinski's membrane-theory analytical equations , the von Mises stress distribution along the meridian, appropriate for metallic yield assessment, is evaluated as a function of local radius of curvature. A Python-based gradient algorithm with multi-start local search minimises peak von Mises stress, driving convergence towards the membrane stress of the adjacent cylindrical shell and eliminating the edge-effect concentration inherent to standard geometries. Each optimised profile is validated in axisymmetric FEA using *LS-DYNA®*. Minimum wall thickness per geometry is determined by enforcing a common maximum stress limit, enabling mass comparison on a structurally equivalent basis.
A case study is conducted for an aluminium alloy tank (E = 70 GPa, ν = 0.33, ρ = 2700 kg/m³,

σ_Y = 210 MPa), radius R = 1000 mm and head depth-to-radius ratio of 0.5. An internal pressure of p = 1 MPa, representative of boil-off pressures of liquid hydrogen tanks, is used. Thickness is resolved in 0.5mm increments, consistent with market metal sheets availability and waDED manufacturing precision. This introduces minor stress deviations relative to the yield limit. Mass is computed and compared across the optimised and three standard profiles (hemispherical, ellipsoidal and torispherical).

3. Results / Conclusions

The standard profiles require a thickness of 3.5 mm (hemispherical), 6.0 mm (ellipsoidal) and 8.5 mm (torispherical), with masses of 59.7 kg, 68.9 kg and 104.5 kg respectively. The optimised requires 5 mm, resulting in a dished end 8 kg lighter than the ellipsoidal and only 1 kg heavier than the hemispherical, without the head-depth constraint imposed by the latter. As shown in Figure 1, the heads exhibit maximum von Mises stresses of 200 ± 10 MPa, reflecting the 0.5 mm thickness discretisation. The optimized meridional profile suppresses the knuckle stress concentration by increasing the radius of curvature near the cylinder junction, and its coincident thickness with the cylinder section simplifies the weld joint. This study demonstrates that optimised dished-end profiles offer meaningful lightweighting potential over standard geometries, while the automated framework provides a reusable basis for further developments, including stress-driven variable wall thickness designs enabled by waDED.

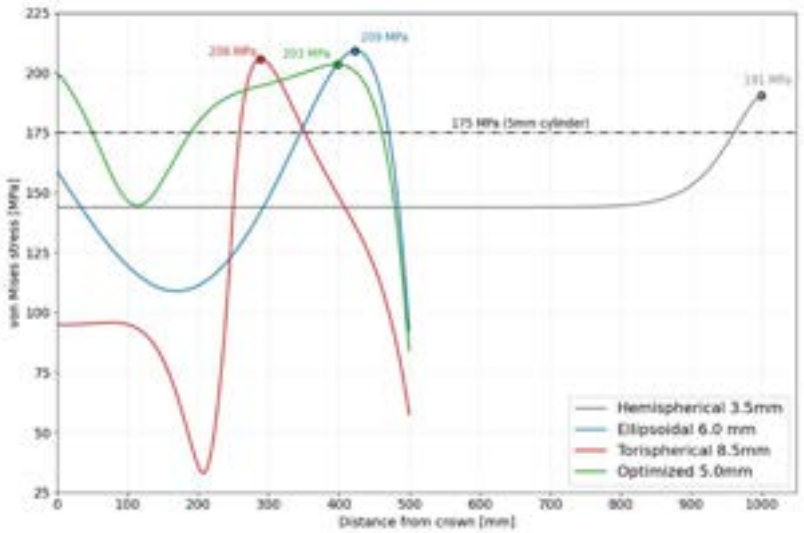


Figure 1: Von Mises stress distribution along the meridian for hemispherical (3.5 mm), ellipsoidal (6.0 mm), torispherical (8.5 mm), and optimised (5.0 mm) dished ends under 1 MPa internal pressure.

Comparative Analysis of Energy Management Strategies for Battery-less Multi-Stack PEMFC Systems in Regional Aviation

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1. Introduction / Objectives

As the aviation industry aims at reducing its carbon footprint, multi-stack Proton Exchange Membrane Fuel Cell (PEMFC) systems offer a scalable, zero-emission solution for regional aircraft. While most current architectures rely on heavy battery buffers to handle transient loads , this study focuses on managing power distribution directly among multiple PEMFC stacks without a secondary energy storage system. In contrast to the most existing studies that typically consider single stacks interfaced via parallel DC–DC converters, a hybrid series–parallel topology is proposed, where PEMFC strings are connected to parallel DC–DC converters. This study focuses on the development and comparative evaluation of Energy Management Strategies (EMS), including rule-based methods with a Model Predictive Control (MPC) approach.

2. Methodology

The power system consists of multiple PEMFC stacks in a hybrid series–parallel topology based on the system described in ref. . The specific layout of the hybrid topology is illustrated in Figure 1. Stacks are connected in series to form strings, which are then interfaced with the DC bus via parallel DC–DC converters. This allows flexible power sharing without a battery buffer. To simulate this system, the PEMFC stacks are modelled using polarization curves via lookup tables, capturing real-time voltage responses. The stack lifespan is evaluated using a multi-regime degradation model that quantifies cumulative voltage loss based on four critical operating conditions: start-stop cycles, idling, load changes, and high-power operation. DC–DC converters are represented as average value model.

Three EMS are developed and evaluated. The rule-based methods include an equal load-sharing strategy and a daisy chain strategy, which provide deterministic baselines for power distribution. These are compared against an MPC approach that optimizes power sharing over a receding horizon. The MPC utilizes a cost function to minimize degradation and hydrogen consumption. A representative regional flight profile, including taxi, take-off, climb, cruise, descent, and landing, serves as the load scenario. Performance is assessed in terms of system efficiency, hydrogen consumption, and accumulated stack degradation. All strategies are evaluated in Modelica under identical operating conditions.

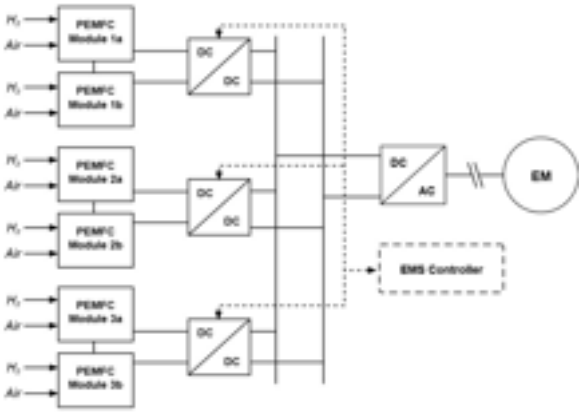


Figure 1. *Topology of multiple PEMFC Systems*

3. Results / Conclusions

Preliminary simulation results indicate that the MPC strategy reduces cumulative stack degradation compared to rule-based baselines by optimizing load sharing. While equal load-sharing and the daisy chain approach offer simple implementation, the predictive nature of the MPC achieves a jointly optimized trade-off between fuel efficiency and stack health across the mission. These initial findings indicate that optimizing stack-level power sharing can enhance system longevity in battery-less aviation applications.

Thermal-Structural Modelling and Optimisation of LH2 Vacuum-Insulated Lattice-Core Sandwich Tank

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1. Introduction / Objectives

Liquid hydrogen (LH2) is a key enabler for zero-emission aviation due to its CO2-emission-free combustion characteristics and its higher volumetric energy density compared to gaseous hydrogen. However, the requirement to be stored at cryogenic temperatures (20 K) necessitates highly efficient insulation systems to minimise boil-off losses. Conventional solutions present a trade-off: insulating foams provide thermal resistance at the cost of increased tank volume, while vacuum-insulated double-wall tanks suppress convection but lack structural load-bearing capability. This study investigates the insulation capacity of a novel design concept for a multifunctional LH2 tank based on a multi-layered, vacuum-insulated sandwich structure with a lattice core. The production of such designs could be made possible, for example, through additive manufacturing processes. A segment the design is illustrated in **Error! Reference source not found.Error! Reference source not found.**. In comparison to conventional designs, this concept occupies the least possible volume of the aircraft fuselage, while offering the possibility for higher operational pressures.



Figure 1. *Cut of the LH2 Vacuum-Insulated Lattice-Core Sandwich Tank*

2. Methodology

For the evaluation of the tank, analytical models for both heat transfer and structural analyses are developed and validated using the finite element method (FEM) in Abaqus. The insulation capacity of the tank is quantified through the boil-off rate (BOR) of the LH2, representing the amount of hydrogen vaporised over a specified period. An analytical method is developed to determine the effective thermal conductivity of the lattice core by implementing Fourier's Law of heat conduction. This subsequently enables the estimation of the tank's BOR using a thermal resistance network. Furthermore, an analytical sandwich model based on the elasticity solutions proposed by Lechnitskii and Kardomateas is implemented to determine the stresses and strains in each layer of the tank structure. These results are then used to evaluate the maximum stresses in the struts by appropriately rotating the stress and strain tensors. To validate the analytical thermal model, a reduced numerical heat transfer model of the tank is developed in Abaqus and analysed under steady-state conditions. The effective thermal conductivity of the lattice layers is also numerically calculated through a solid model of the unit cell. In parallel, the tank is assessed under the structural loads arising from the operational pressures. For this purpose, a corresponding numerical structural model is implemented in Abaqus and analysed under static internal pressure loading for validation purposes. In the numerical model, the lattice struts are represented as Bernoulli beams, while periodic boundary conditions are applied, depending on the tank model results, to capture the repetition of the unit cells across the tank surface. Finally, the tank design is optimised using the validated analytical models described above. Geometric parameters, including the strut diameter, unit cell dimensions, number of layers and tank contour are varied with the aim of minimising the BOR and structural mass while maintaining the structural integrity.

3. Results / Conclusions

The present study demonstrates the feasibility of a vacuum-insulated lattice-core sandwich tank for LH2 storage, capable of sustaining the structural loads arising from internal pressure while minimising both BOR and structural mass. The developed analytical models achieve computational times 3–4 orders of magnitude lower than the corresponding high-fidelity numerical models, depending on the tank dimensions, thereby significantly accelerating the optimisation process. This enables the rapid identification of lightweight tank configurations with minimal thermal losses within only a few minutes of computation. Furthermore, the load-bearing capability of the lattice core facilitates the development of non-rotationally symmetric tank geometries that can be conformally integrated into the aircraft structure.

Numerical study to assess the crashworthiness of a composite conformal LH_2 tank

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Royal Netherlands Aerospace Centre (NLR), Netherlands

1. Introduction / Objectives

Liquid hydrogen (LH_2) is a promising energy carrier for future aircraft to reach net-zero CO_2 emissions. LH_2 comes however with challenges like storage at -253 °C and requires very good

insulation to prevent excessive boil-off and pressure built-up. Due to its low volumetric energy density, it requires about 4 times more volume than jet fuel potentially leading to large storage tanks. A safety concern is hydrogen's low ignition energy, flammability and leakage risk, the latter being especially true for composite LH_2 tanks. Crashworthiness of a composite LH_2 tank is therefore very important and required for certification. The main objective of the Clean Aviation CRYOSTAR project is to design, develop and demonstrate an advanced tank attachment and restraint system for a LH_2 tank installed in the rear section of a CS-25 aircraft fuselage capable of absorbing crash loads by using an innovative retention and energy absorbing system.

2. Methodology

The design, development and demonstration of the LH_2 tank attachment and restraint system will be achieved by combining numerical analysis and physical testing. In the current study the crashworthiness potential of the composite conformal LH_2 tank design shown in Figure 1, which comes from the Clean Hydrogen COCOLIH_2T (COmposite COnformal LIquid H_2 Tank) project **Error! Reference source not found.**, is checked with numerical analyses in Abaqus by applying dynamic crash loads to the outer tank flange. The outer tank flange will be used to connect the tank to the rear fuselage section with a novel retention and shock absorption system. Also operational pressure load cases will be analysed to check if the updated outer tank design needs to be revised or not and the outer tank Finite Element (FE) model will be validated with test data from earlier performed pressure tests. Different crash load cases with the tank will be analysed to aid the design of the new retention and crash absorption system for the tank. With these numerical crash analyses, it will also be checked if the current tank spacer design can resist the crash load of a vertical drop test with the tank installed in the rear fuselage section.



Figure 1. *Composite conformal LH_2 tank design used in the crashworthiness study*

3. Results / Conclusions

The numerical crash analysis results of the composite LH_2 tank will be used to assess the tank's crashworthiness and will help to size the new retention and crash absorption system for the tank. The simulation results will also help to determine if the current tank spacer design can survive a vertical drop test with the tank installed in a rear fuselage section or need to be modified or redesigned. The numerical results of operational pressure load cases will help to

improve the outer tank design if needed and the outer tank FE model will be validated with test data from pressure tests.

Capacity Scale Effects in Power-to-Liquid Sustainable Aviation Fuel Production: A Techno-Economic and Project-Finance Assessment

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1. Introduction / Objectives

Aviation is among the hardest-to-abate transport sectors due to its dependence on high energy-density fuels and limited near-term electrification potential [1]. Although aviation represents around 2–3% of global energy-related CO_2 emissions, its total climate impact is higher when non-CO_2 effects such as contrails and NOx are considered [2]. Sustainable aviation fuels are therefore central to decarbonisation, yet bio-based pathways such as HEFA and AtJ face feedstock, land-use and scalability constraints [3]. Power-to-Liquid e-SAF, produced from renewable hydrogen and captured CO_2, offers a scalable long-term alternative, but remains limited by electricity, electrolyser, CO_2-capture and financing costs [4–6]. In this context, the study compares two PtL-SAF plant scales to assess their techno-economic feasibility and bankability, using Türkiye as an illustrative data context while developing a methodology adaptable to other regions and input assumptions.

2. Methodology

The study develops a deterministic, bottom-up techno-economic and project-finance model in Microsoft Excel to evaluate PtL-SAF production. The methodology links technical sizing, CAPEX, OPEX, product revenues, financing structure, income statement, annual cash flows and investment metrics within a single transparent calculation chain. This structure is selected because it allows assumptions to be modified, supports comparison of alternative scale and financing scenarios, and reflects feasibility-stage project-finance practice.
Two plant-scale scenarios are analysed: a Large-scale plant producing 20,000 t SAF/year and a Mega-scale plant producing 100,000 t SAF/year. The purpose of this comparison is not only to estimate production economics, but also to examine how scale affects the practical implementation of e-SAF projects, where global discussions increasingly focus on technology bottlenecks, cost barriers, SAF mandates and the realism of future deployment pathways.
Both scenarios use the same process configuration: renewable electricity supply, alkaline electrolysis for hydrogen production, direct air capture for CO_2 supply, reverse water-gas shift conversion, Fischer–Tropsch synthesis and downstream upgrading. Main technical assumptions include 0.8 kg H_2 and 3.1 kg CO_2 per kg SAF, with renewable electricity capacity sized according to electrolyser demand and regional solar-resource conditions.
Capital expenditure is estimated through a component-based approach covering renewable electricity, electrolyser, direct air capture and RWGS–FT–upgrading blocks. Working capital is added as 12% of direct CAPEX. Operating expenditure includes renewable-system O&M, fixed plant O&M, DAC operation, catalyst/sorbent/membrane replacement, water, insurance and administrative expenses, with annual costs escalated using a 2% USD inflation assumption. Türkiye-specific data are used mainly for the initial regional case, including selected renewable-resource and tariff-related inputs, while general investment and inflation assumptions are expressed in USD to improve transferability.

Revenues are calculated from SAF, diesel and naphtha streams, with SAF treated as the main product and diesel/naphtha as Fischer–Tropsch co-products. The financing module applies scenario-specific debt–equity structures. These ratios are adjustable, allowing the model to test alternative investor strategies, public-support mechanisms or concessional-

finance structures. Project performance is evaluated using equity NPV, equity IRR, payback period, WACC and debt-service coverage logic. The methodology therefore provides an initial decision-support framework for comparing deployment pathways and can be refined with deeper regional datasets for more precise future assessments.

Table 1. Scenario definition and core modelling assumptions

Parameter	Large-scale plant	Mega-scale plant
SAF production capacity	20,000 t/year	100,000 t/year
Process route	AWE–DAC–RWGS–FT	AWE–DAC–RWGS–FT
Evaluation metrics	NPV, IRR, payback, WACC	NPV, IRR, payback, WACC

3. Results / Conclusions

The results show that PtL-SAF production in Türkiye is technically plausible but strongly constrained by capital intensity and financing structure. The total investment requirement is estimated at USD 1.03 billion for the Large-scale plant and USD 5.97 billion for the Mega-scale plant. Under the assumed financing conditions, the Large-scale case generates a positive equity NPV of USD 637.87 million, an equity IRR of 97.92%, and an equity payback period of approximately two years. In contrast, the Mega-scale case generates a negative equity NPV of USD −198.77 million and an equity IRR of 8.31%, below the 12% target return. These findings indicate that larger PtL-SAF plants do not automatically provide stronger bankability, because key cost blocks scale nearly linearly. A phased deployment strategy, beginning with intermediate-scale plants and supported by SAF mandates, long-term offtake agreements and concessional finance, is therefore recommended.

APFEL – Analysis of Hydrogen Permeation Properties of Fiber-Reinforced Polymer Composites

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1. Introduction / Objectives

Hydrogen is considered a key energy carrier for future sustainable aviation concepts. Type V pressure vessels made entirely of fiber-reinforced polymer (FRP) composites offer significant weight-saving potential for hydrogen storage. However, the influence of fatigue-induced damage on the hydrogen barrier performance of FRP materials is not yet sufficiently understood.

The German aviation research project APFEL (LuFo VI-3) investigates the relationship between cyclic damage accumulation and hydrogen permeation in carbon-fiber-reinforced (CFRP) and glass-fiber-reinforced polymers (GFRP). The project's innovation lies in combining X-ray refraction-based damage characterization, hydrogen permeation measurements, and cyclic fatigue loading within a single experimental framework. This approach enables a systematic investigation of how microstructural damage evolution may affect hydrogen

barrier performance and provides essential knowledge for the development of lightweight composite hydrogen storage systems.

2. Methodology

The APFEL project combines hydrogen permeation measurements, X-ray refraction-based damage characterisation, and cyclic fatigue loading to investigate the relationship between damage evolution and hydrogen barrier performance in fibre-reinforced polymer composites. The experimental strategy is based on repeatedly applying these methods to the same specimen throughout progressive damage development. The experimental procedure is illustrated in Figure 1.

The investigated material system consists of the epoxy resin RIM1040 combined with two industrially relevant glass-fiber reinforcements and two industrially relevant carbon-fiber reinforcements. For each reinforcement type, three laminate configurations are manufactured and tested. The laminate designs are selected to represent a broad range of mechanical loading conditions, including fiber-dominated tension, transverse tension, shear-dominated loading, and multiaxial stress states. To ensure comparable damage progression, fatigue load levels are determined individually for each specimen series based on prior S–N investigations.

Cyclic loading is performed under tension-tension conditions with a load ratio of R = 0.1. The selected stress levels ensure that 200,000 load cycles are reached with a survival probability of 99%. Hydrogen permeation measurements and X-ray refraction analyses are first conducted on the undamaged specimens. Subsequently, the specimens are subjected to cyclic loading and re-evaluated after every 50,000 load cycles until a total of 200,000 cycles is reached. X-ray refraction measurements are performed in the same specimen area used for permeation testing, enabling a direct comparison between local damage evolution and barrier performance. Hydrogen permeation behavior is characterized by recording Arrhenius diagrams over a temperature range from 25°C to 70°C. This approach enables the determination of temperature-dependent permeation characteristics and their evolution during fatigue loading.

The selected laminate configurations and fatigue loading scenarios are designed to represent service conditions relevant to both high-pressure hydrogen storage systems and aerospace structures. In particular, the investigated lifetime of up to 200,000 cycles covers and exceeds typical aircraft operational requirements, allowing the relationship between damage accumulation and hydrogen permeation to be assessed over a representative service life and beyond.

3. Results / Conclusions

Initial results include successful specimen manufacturing, hydrogen permeation measurements on the epoxy resin system RIM1040, and baseline permeation measurements on undamaged CFRP and GFRP laminates. Figure 2 presents Arrhenius diagrams obtained from preliminary permeation measurements on undamaged CFRP and GFRP laminates as well as on a GFRP specimen after 200,000 fatigue cycles.

Furthermore, fatigue investigations have been performed to define suitable loading horizons for controlled damage initiation in composite specimens. The developed methodology establishes the experimental foundation required to quantify the relationship between fatigue-induced damage and hydrogen permeation behavior. Ongoing investigations will provide insights into how different damage states affect the barrier performance of composite materials. The results are expected to support the qualification and design of lightweight Type V hydrogen storage systems for future aerospace and mobility applications.

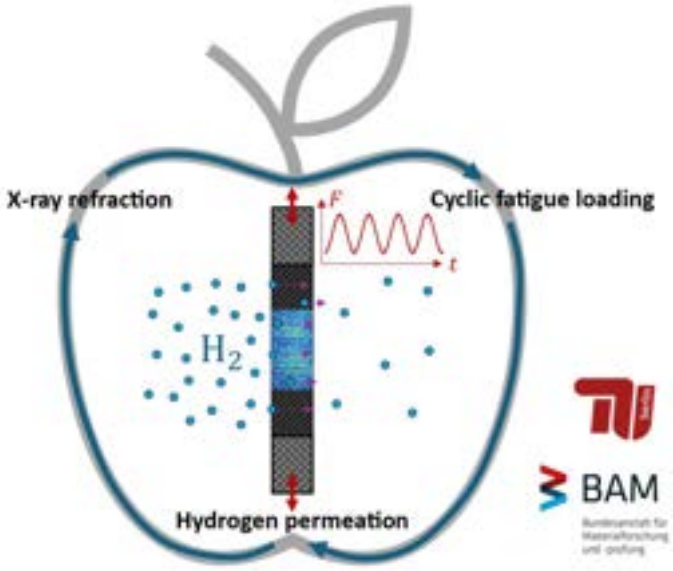


Figure 1. *Experimental methodology used in the APFEL project, combining X-ray refraction analysis, hydrogen permeation measurements, and cyclic fatigue loading.*

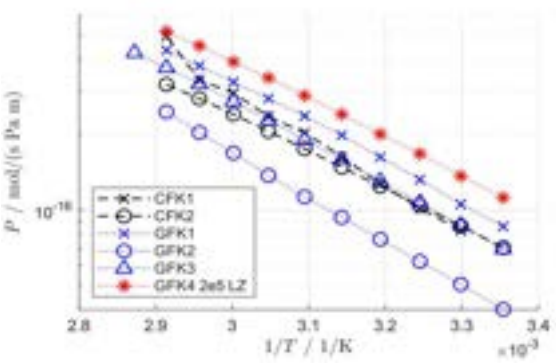


Figure 2. *Arrhenius diagrams of hydrogen permeation measurements obtained on undamaged CFRP and GFRP laminates and on a GFRP laminate after 200,000 fatigue cycles.*

CryoTOAD – An Open-Source Cryogenic Tank Thermal model for Overall Aircraft Design

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1. Introduction / Objectives

This conference paper presents an open-source cryogenic tank thermal model (CryoTOAD) for transonic and hypersonic overall aircraft design applications.
CryoTOAD enables the study of flat cylindrical and multiple-bubbles tanks. Multiple Layer Insulation (MLI) system with variable thickness can be studied. CryoTOAD aims to predict the heat transfer inside a cryogenic tank throughout a typical transonic or hypersonic flight. The model is encoded in FORTRAN for the best trade-off between accuracy and computational efficiency. CryoTOAD can be used as a module in any Overall Aircraft Design, and its main objective is to reduce the level of discrepancies on cryogenic tank thermal performances that play an important role in the overall performance of a Hydrogen aircraft. The paper is structured as follows: Section II presents the overall methodology used and implemented in CryoTOAD to model the heat transfer inside the multilayer insulation (MLI). The model is validated upon canonical experimental examples of the literature to highlight the different features proposed and their accuracy (Natural convection, non-linear heat conduction, ice formation, water vapour convection etc). Section III describes how the thermal stratification of liquid and ullage is modelled by CryoTOAD. Section IV proposes a coupled validation of the MLI and liquid ullage models using experimental data from a 25 cubic meters tank of the US-Airforce (cf Figure 1). Section V presents the overall computational performance of CryoTOAD.
Nota-Bene: The model will be available on a Git-Repository as well as the experimental data used to validate CryoTOAD.

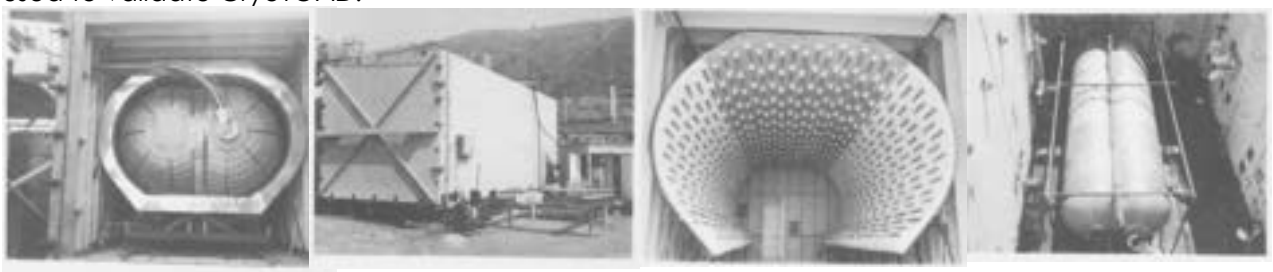


Figure 1. *US-Airforce Flight Dynamic Laboratory, 25 cubic meters hypersonic tank used for CryoTOAD experimental validation. From left to right: Tank with it insulation blanket; exterior view of the flight simulation chamber; radiation shield; structural bench.*

2. Methodology

The heat transfer inside the MultiLayer Insulation system is captured by solving the Darcy Forenheimer equations, using a transient extension of a Semi-Implicit Pressure Linked Equation solver (PIMPLE) on a collocated grid (adapted from [1]. Natural convection inside porous material can be captured, as well as non-linear conduction and radiation, moisture pollution and ice formation/sublimation. The solver can be accelerated if natural convection is not present and there is no moisture pollution (momentum equations are degenerated).
The heat transfer and thermal stratification are captured using enthalpy updates on horizontal liquid and ullage nodes. Liquid and ullage turbulent natural convection boundary layers are modelled to capture the heat transfer towards the top nodes. Boil-off is triggered on each node by checking the enthalpy of saturation at the given tank pressure. At each time step, the venting mass rate is computed to remain below the operation pressure of the tank. Finally, slush hydrogen can also be modelled as it could be an interesting lever to improve the tank gravimetric index.

3. Results / Conclusions

Figures 2 and 3 highlights the current CryoTOAD predictions' performance using the experimental data from the US Air Force Flight Dynamic Laboratory [2] on a Hypersonic 25 cubic meters hydrogen tank exposed to strong heating

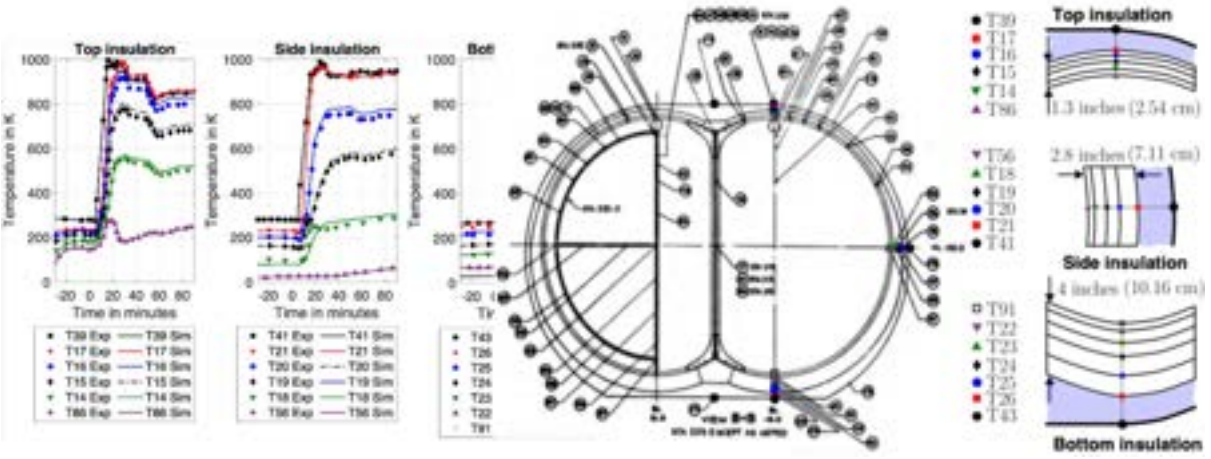


Figure 2. *Heat transfer inside the tank insulation system, at bottom, side and top. CryoTOAD predictions versus experimental measurements. Right figure shows the temperature probes locations*

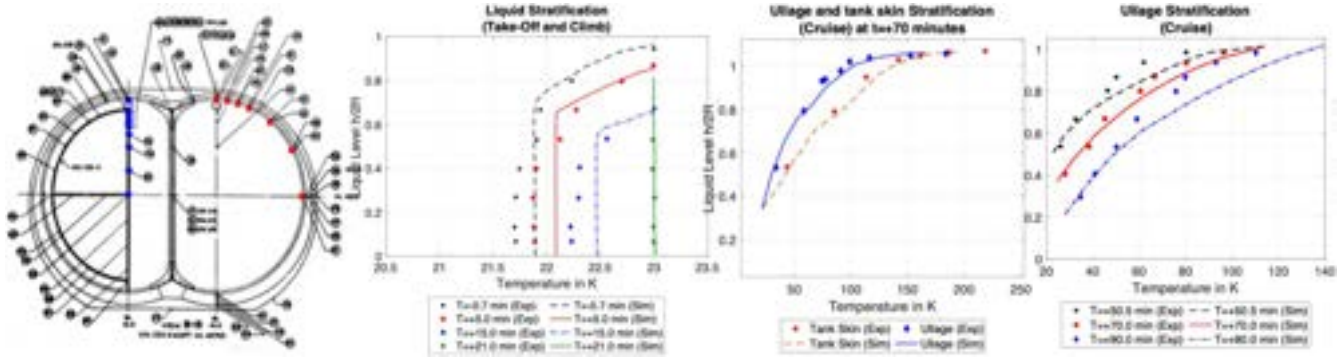


Figure 3. *Thermal stratification of liquid and ullage inside the tank during the mission. Temperature difference between gas and tank skin. CryoTOAD predictions versus experimental data. Left figure shows the different temperature probes locations.*

Impact of very fast events and hazards on the sustainability of aerospace structures

Chaired by:
Prof. Christine Espinosa (ISAE-SUPAERO, France), Prof. Alain Merlen (Lille University, France) & Prof. Michel Arrigoni (ENSTA/IRDL, France)
Supported by EUCASS

Inputs for laser solutions for space debris mitigation or space transportation

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1. Introduction / Objectives

Laser propulsion could provide a technical solution to problems related to the transport or movement of space objects (i.e., satellites, space debris) by depositing tailored laser energy onto the object surface . Among the various materials studied for space applications and their ability to generate thrust under laser irradiation , several families stand out due to their adaptable physical and chemical properties. Depending on their composition and structure, some materials can efficiently absorb laser energy and convert it into motion in the form of mechanical impulse through the material ablation . Beyond their energetic response, practical considerations such as stability and compatibility with the space environment also play a key role in material selection to ensure reliable assessment of propulsive performance in vacuum. These characteristics point towards materials suitable for laser propulsion studies .

2. Methodology

The experimental study of laser propulsion via the impulse transmitted to objects by laser irradiation allows for the evaluation of material and laser requirements necessary for the potential implementation of space solutions for various operations in space (orbit correction, avoidance, atmospheric re-entry, etc.). An experimental protocol is presented to study the response of materials such as carbon/epoxy composites, graphite, ceramics, or engineering polymers to continuous laser irradiation. First, the potential loss of material integrity under different laser parameters is addressed: this mainly concerns surface ablation for continuous lasers and the assessment of perforation limits. Next, for laser irradiation conditions below the material deterioration thresholds, the propulsive capability of laser irradiation is evaluated using experimental setups to observe gases from the ablation plume or to induce movement of objects (i.e., rotation) in vacuum with varied laser parameters. The extracted measurements allow for the determination and analysis of key characteristic quantities such as the impulse coupling coefficient (C_m)—the ratio between the pressure generated by the laser shot on the surface and the beam intensity . Finally, a discussion is presented on the use of these experimental data to confirm the established results and to explain the mechanisms enabling thrust generation.

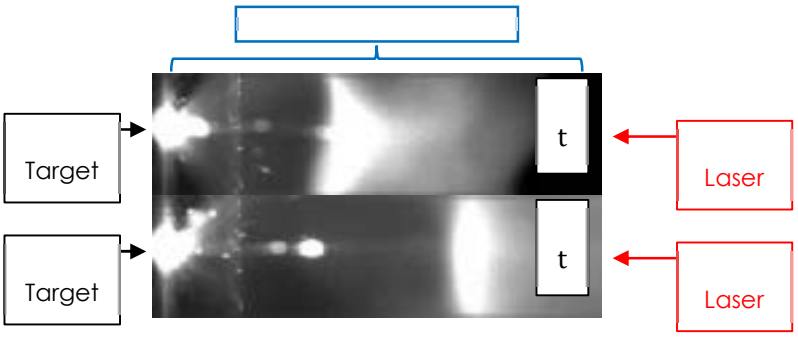


Figure 1. *Chronology of the jet expansion with a carbon composite CFRP (10ms pulse, 10.3µm, 10kW) - Laser irradiation is providing by right to the target creating a vapor plume with a high ejection speed.*

3. Results / Conclusions

This study explores the mechanics of **laser ablation propulsion** under quasi-continuous irradiation, focusing on the relationship between plume dynamics and thrust efficiency. By utilizing direct momentum measurements alongside high-speed diagnostics, we identified that carbon-based materials are particularly effective, yielding momentum coupling coefficients of approximately **150 µN/W**. A key finding of the research is the structural nature of the ablation plume. The study establishes a formal analogy between the laser-induced plume and **under-expanded supersonic jets** found in classical propulsion . This framework allows for a more sophisticated interpretation of how laser-material interactions translate into measurable propulsion performance. Despite the promising efficiency levels, the study highlights critical hurdles for practical space applications, including **thermal management**, **material durability**, and **system scalability**. Future research must refine diagnostic techniques and explore diverse materials to optimize the robustness and efficiency of laser-based thrusters for long-term mission viability.

Aeronautical composite structure dismantling using laser shock processing

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1. Introduction / Objectives

Carbon Fiber Reinforced Polymers (CFRP) are strong and light materials which see a growing use in aeronautical structures. Although they can survive strong aggressions such as hypervelocity impacts and lightning strikes , their recycling, maintenance and repair remain a challenge. Laser shock is already being used by aircraft manufacturers for quality control and localized dismantling but theses processes are not yet applicable to large structures. This paper studies the possibility of disassembling large Carbon Fiber Reinforced Polymer composite structures by creating a large homogeneous delamination from a series of laser

shocks of smaller radius arranged in a grid pattern. After selecting the appropriate energy density level and grid size, the proposed protocol is conducted on a disk-shaped sample. The damage position variability is studied and the microtomographic analysis of the post-mortem sample is used to validate the methodology. Strategies to improve the homogeneity of the delamination are discussed.

2. Methodology

Laser pulse induces a shockwave in the structure, generating tensile stress when reflecting on the rear face of a structure. The pulse length and intensity enable the control of the position of the created delamination in the thickness. However, to produce an energy density high enough to produce delamination, the laser has to be focalized on a few square millimeters. This work studies the feasibility of creating large delamination from several laser shocks arranged in a grid pattern, notable the homogeneity of the induced delamination and the coalescence of the delamination areas produced by multiple sequenced laser shocks. The Carbon Fiber Reinforced Polymer composite laminate of interest in a thirteen plies unidirectional composite manufactured courtesy of Airbus with a stacking of $[45/-45/90/45/-45/0/90_{0.5}]_s$ for a total thickness of 1.651mm. These homogeneity and coalescence features are first studied separately: several independent laser shocks are produced at different energy density and the homogeneity of the damage induced is analyzed. Using the energy density corresponding to the most homogeneous delamination, the coalescence is studied by performing several laser shocks aligned in the 0° direction (to have a midpoint between the 45° and -45° direction of the first two plies) and spaced by 5 mm which is slightly above the ablation diameter of 3 mm to prevent any overlap. The preliminary results are used to refine the energy density and grid characteristic length of the feasibility test which is performed on a Φ35 sample. The sample is subjected to fifty-seven shots, and the post-mortem analysis is performed using a micro-tomography with a 18 µm characteristic length. Several delamination patterns are observed. An hypothesis linking the impact grid pattern, the overlap between adjacent shots, the energy density and the observed damage is formulated.

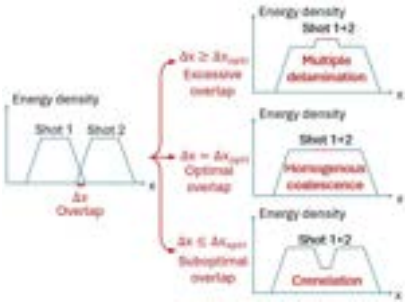


Figure 1. *Hypothesis linking the overlap between impacts and the coalescence of the delamination areas.*

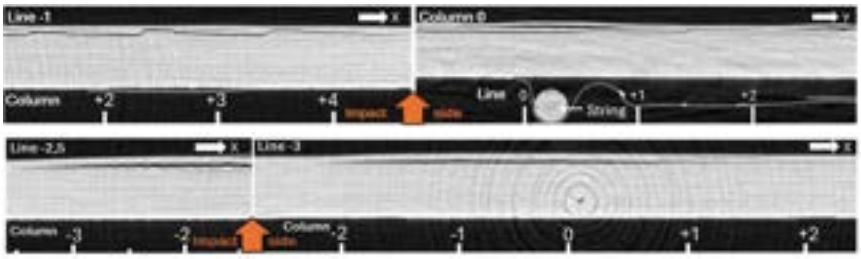


Figure 2. *Side-views of the tomography analysis of the feasibility test. The rule indicates the position of the impact relative to each other. The main damage patterns are shown (from top-left to bottom-right): crenelated delamination, multiple delamination through the thickness, wavy homogeneous delamination and homogeneous delamination.*

3. Results / Conclusions

The preliminary coalescence study shows no overlap between the delamination area, implying that an overlap between the ablation crater is mandatory to produce coalescence of damage. The tomography of the feasibility test shows patterns that can be linked to the overlap between adjacent shots. Assuming damage is cumulative, overlapping impacts enable the summation of local applied energy density (Figure 1 & 2): crenelated delamination appears when the overlap is below the optimal length, homogeneous delamination when the overlap is optimal and multiple delamination through the thickness appears when the overlap is above the optimal length. The optimal length may not only depend on the laser setup but also on the structure due to its orthotropic behavior. Optimizing the overlap between laser shots may enable the dismantling, replacing or repairing of large composite structures by creating structure wide homogeneous delamination area, increasing the lifetime of the structure or improving its recyclability.

Numerical modelling of the thermomechanical loading induced by electric fault arc in aeronautical electrical network

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In the aeronautical industry, high voltage and direct current networks (HVDC) are introduced in the aircraft electrical system to enable the integration of new sustainable propulsion technologies. This can increase the hazardousness of electric fault arcs. The latter are strong discharges that generate a thermal plasma of a transient and erratic nature. This phenomenon can induce physical damage to the aircraft's structure and its critical systems. Part of the electrical energy injected into the arc is dissipated as heat because of the Joule effect. The fast heating of a small volume of air generates an overpressure wave. The remaining heat is transferred into the environment by radiation and convection and to the cables by conduction. Under heating, cables may be subject to ablation, leading to the projection of molten metal droplets onto the surrounding structure . The present study focuses on the numerical modelling of the coupled, thermal and mechanical effects caused by the radiative flux and the overpressure wave.

A numerical model is developed using the finite element code Abaqus explicit. The case study consists of a 100x100x1 mm^3 aluminum plate subject to thermal and mechanical loadings representative of a low energy electric fault arc distant from 200 mm. The plate is fixed on an edge by a steel support, and convective exchanges are imposed between the plate's surfaces and the environment. Far away from the plate, the arc is viewed as a point - like radiative source, and the radiation distribution has a spherical shape. The radiative flux to be applied to each element, $q_{ray}(r,t)$, is determined by dividing the arc's total radiative power $Q_{ray}(t)$ (dotted line on the Figure 5a, data from literature) by the surface area of a sphere of radius *r*, intersecting the elements of the plate, see Figure ***5***b. The radiative flux is applied via a user routine (VDFLUX). The overpressure time and space dependence is described through the Friedlander equation and calibrated using Morsel *et al.* experimental data . This allows to determine the incident overpressure in the air $P_i(r,t)$ as a function of the electric energy E_{elec}. In this study, a spherical propagation of the pressure wave is considered, see Figure 5b. Figure 5a (solid line) shows the temporal evolution of the transmitted pressure applied $P_t(r,t)= 2P_i(r,t)$ on the plate's surface. The resulting mechanical load is applied via a user routine (VDLOAD). Figure 6a shows the equivalent stress σ_{eq} field at different instants during the interaction of the overpressure wave with the plate's front face. During the first few hundredths of ms, the stress wave radially expands from the plate's center toward the plate's edges. At the instant t=0.376 ms the stress wave reaches the area where the steel support is located, leading to stress concentration. After an analysis of the σ_{eq} stress field, two critical elements are identified: the one that is first subjected to the overpressure wave (element at the plate's center in Figure 6a), and the one which is subjected to the stress concentration at an advanced time (element in contact with the steel support in Figure 6a). Figure 6b shows temperature (dotted lines) and σ_{eq} (solid lines) temporal evolution at the two critical positions: the node/element of the center of the plate (in gray) and the node/element in contact with the support (in black). After the overpressure impact, the plate is excited at 90.33 Hz (a frequency close to one of the structure's natural frequencies). For this reason, high frequency oscillations are observed for $\sigma_{eq}(t)$ on both analyzed elements (solid lines Figure 6b). The maximum value of σ_{eq} is reached some ms after the arrival of the overpressure load, while the maximal temperature is reached at 800 ms. The maximal value of σ_{eq} is of 53 MPa for the center of the plate and 46 MPa at the support zone, i.e. much lower than the yield stress of the plate material. On the other hand, the heating is only 4°C for both nodes, i.e. very low. This numerical study allows a better understanding of the combined effect of radiative flux and overpressure wave induced by a low energy electric fault arc. In works in progress, electric fault arcs closer to the plate and of higher energy are considered. Numerical results will be compared with available experimental results.

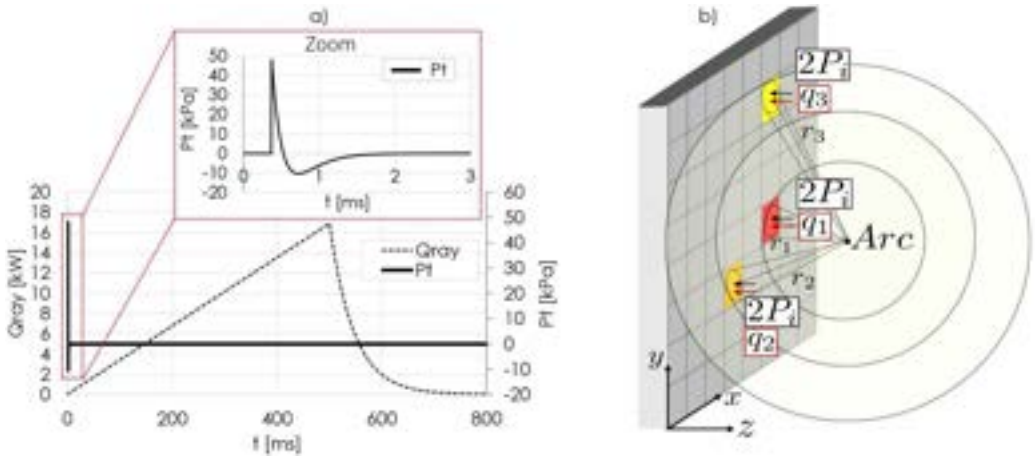


Figure 5 a) Temporal evolution of Q_{ray} (dotted line) and P_t (solid line) b) Application of the equivalent thermal and mechanical load

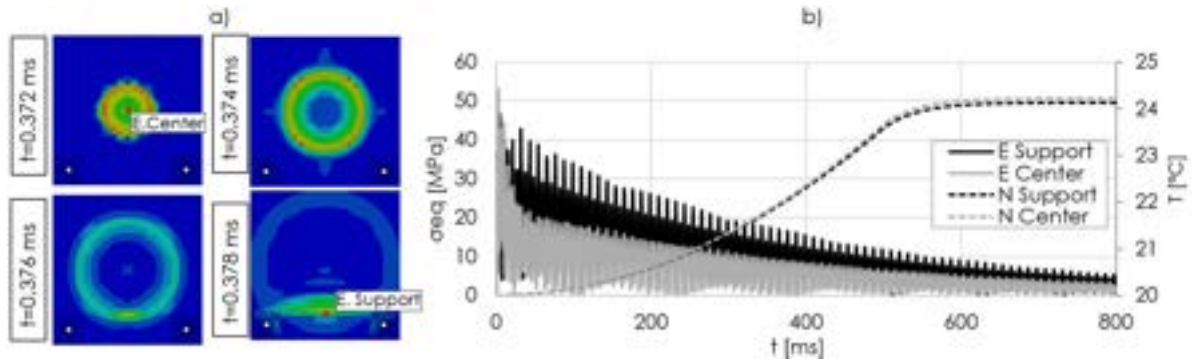


Figure 6 a) Qualitative σ_{eq} map after the overpressure impact b) Temperature (dotted lines) and σ_{eq} temporal evolution (solid lines) at 2 positions of the plate's front face: center (in gray) and support contact zone (in black)

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Laser Ablation Propulsion for space debris removal: impulse generation by aluminum and role of irradiation parameters

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1. Introduction

Earth orbit is now fundamental for communication, observation and scientific exploration, and is now becoming crowded, with hundreds of new satellites deployed every year. As a drawback, the intense exploitation of Earth orbit also led to the formation of a huge population of space debris, coming from ended missions and collisions.

The motion of such objects is often not well known, making them a threat for new or

operating missions: active removal of space debris is therefore required.
Laser ablation propulsion (LAP) offers a promising solution for space debris deorbiting, allowing the generation of a mechanical impulse on a far object by irradiating it with an intense laser pulse. LAP therefore opens the possibility to deorbit an object from long distances, avoiding any mechanical contact.
In order to understand the applicability of LAP, an experimental investigation of its performance in representative cases is required.

2. Methodology

This work presents a systematic assessment of impulse generation by laser ablation of aluminum, taken as a representative debris material. Impulse generation is achieved by irradiation with a Nd:YAG laser, and is measured by using a specifically designed ballistic pendulum operating in vacuum, as presented in Figure 1.
Several parameters affecting impulse generation are taken into consideration. Two different laser wavelengths are used: 266 nm and 532 nm, and the variations on impulse generation by multiple irradiations of the same regions are considered. Additionally, the role of laser incidence angle is also investigated.
All these parameters are likely to play a role in space debris deorbiting by LAP so that their assessment is required to clarify the applicability of this technique.

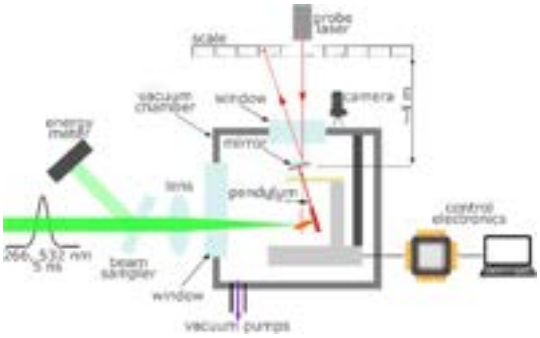


Figure 1. *Scheme of the experimental apparatus.*

3. Results and Conclusions

Obtained result highlight that the effectiveness of LAP for space debris deorbiting is a function of different parameters. All the considered parameters play a relevant role in impulse generation. In particular, the consecutive irradiation of the same region leads to a reduction in impulse generation, showing that care must be taken when estimating the operation capability of LAP. In a real case operation, moreover, these parameters may not be well known, further complicating the estimations.
Nevertheless, LAP remains a really promising solution for the deorbiting of small space debris, for which it is still difficult to find viable solutions.

Acknowledgement: This study was carried out within the Space It Up project and received funding from the ASI and the MUR—Contract no. 2024-5-E.0-CUP no. I53D24000060005.

Assessing Post Explosion Conditions in Space Launcher Breakup Scenarios for Debris Prediction

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1. Introduction / Objectives

The increasing frequency of space launches has raised concerns about the sustainability of the orbital environment, particularly due to the risk of in-orbit explosions.
The fragmentation of launchers due to a failure of engine, structural or control systems is a significant contributor to the growing population of orbital debris , with the initial velocity of ejected fragments playing a critical role in determining their long-term orbital evolution and collision risk for future flight.
Accurate modeling of these velocities is essential for predicting debris dispersion and assessing the potential hazards to active spacecraft. They are usually obtained with engineer tools based on models like Baker's where the post-explosion conditions are critical inputs.
This study focuses on determining these initial conditions for several explosion models, providing essential data for subsequent velocity and trajectory analyses. By characterizing the initial state, we aim to improve the accuracy of debris dispersion predictions and contribute to more effective debris mitigation strategies.

2. Methodology

Numercial simulations are conducted using blastFoam code to compute the propagation of the blast wave resulting from a spherical explosion. 2D, axisymmetric, inviscid Euler equations are solved and adaptative mesh refinement is used to efficiently handle large domains. Maximum overpressure and impulse are reported. Several explosion scenarios are compared:
The baseline configuration involves the detonation of a high explosive charge (TNT), a widely used reference in blast studies despite its known limitations. The charge is center detonated, using a linear activation model based on a predetermined detonation velocity. JWL equation of state for detonation products and ideal gas equation of state for surrounding air reproduce experimental data with high fidelity.
The second configuration examines a modified post-detonation configuration where the flow is initially at rest and the thermodynamic state is uniform, using Chapman-Jouguet parameters for pressure and temperature. This setup mirrors the initial static state assumed in 0D models (e.g., Baker-like models), aiming to highlight potential differences in blast wave development and TNT equivalent.
The third configuration simulates the constant volume explosion of a stoichiometric gaseous H_2/O_2 mixture initially at 100K in a 6.1-m (20 ft) radius sphere at 33 bar (480 psi). This case aligns with the cryogenic explosion model used by NASA where gaseous products are model by a multispecies mixture with the ideal gas equation of state.

3. Results / Conclusions

Preliminary results indicate minimal differences between the first and second configurations. We expect that the overpressure between configuration 3 will yield a significantly distinct pressure profile in the near field compared with a calibrated configuration 1 with a TNT equivalent in the far-field. This discrepancy is expected to have a substantial impact on the initial velocity of fragments.

Modelling of hypervelocity impacts of debris using a meshless gamma-sph scheme

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1. Introduction / Objectives

Satellite vulnerability analysis of orbital debris and micrometeorite impacts treated at external sur-faces is relatively simple but provides unacceptable and unrealistic levels of risk. The analyses are now carried out at the level of the internal surfaces (equipment skins). Several models are available to study the vulnerability of internal surfaces, but they all face poor or non-existent management of fragment tracking. For the simplest impacts (aluminum ball type versus aluminum plate), the results obtained are close to experiment. However, they do not directly provide the debris cloud model (typically mass of debris and speed in each direction) for a vulnerability analysis on a target placed beyond in the path of the Debris. The aim of this research is to explore innovative fragmentation modelling solutions in the context of hypervelocity impacts of debris.

2. Methodology

This study has led to the development of a numerical approach to processing fragment identification from a multi-plate hypervelocity impact. One of the hard points of standard SPH approaches is the model size (number of particles). Indeed, if the number of particles becomes too large, the calculation times drastically increase limiting then their industrial use. Highlighted in a recent thesis , the Gamma-SPH approach developed by ABSTRAO in partnership with Jean-Paul Vila provides robust results of fragment clouds in reasonable computation times through GPU parallelization.

3. Results / Conclusions

Through this work, a complete and detailed study of multi-plate hypervelocity impacts is successfully performed with Gamma-SPH Solver. Thanks to the robustness and accuracy of the Gamma-SPH approach, ABSTRAO can properly reproduce the experimental results. Particularly, the influence of the impact velocity (in the 2-8km/s range) on the multi-impact and perforation of a secondary plate is correctly handled. The combination with an efficient fragment detection algorithm makes it possible to perform an accurate fragment analysis on the fly, and to exploit the data with in-house codes. Also, the benefit from GPU acceleration significantly reduces computation time allowing to meet industrial needs and to consider real orbital structures. It should be noted that the developments carried out are directly

exploitable in the context of hypervelocity impact or fragmentation applications for space applications as well as military applications.

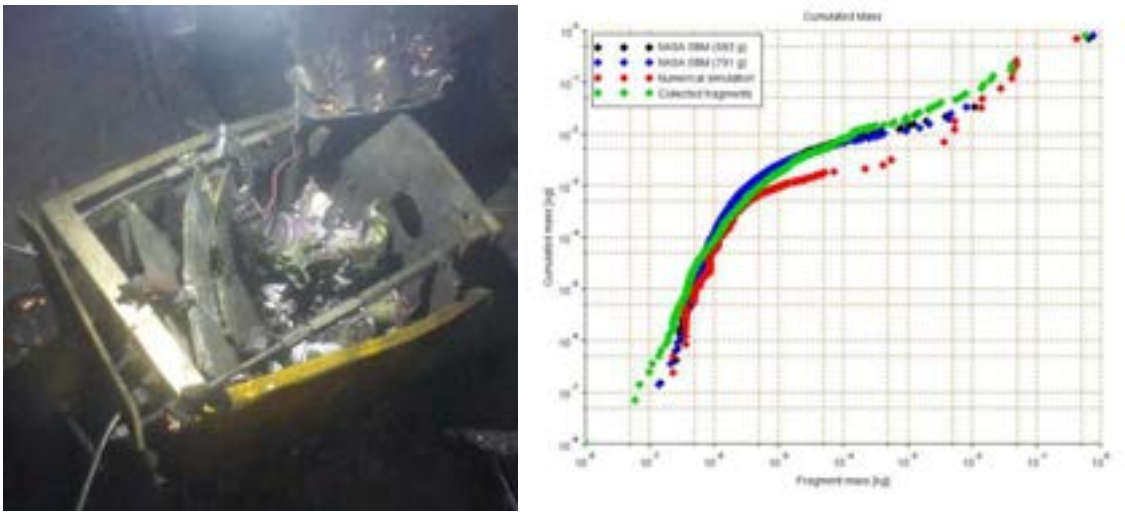


Figure 1. *Left: Impact on nano satellite, final damaged structure [From CNES]. Right: Fragment analysis comparison between reference NASA breakup model, experimental study and Abstrao numerical simulation.*

Data-Driven Engineering Design for Aerospace Manufacturing and Systems

Chaired by:
Prof. Timoleon Kipouros (Cranfield University, UK) & Prof. Ola Isaksson (Chalmers University of Technology, Sweden)

Learning-based enhancement of augmented Lagrangian coordination for distributed multidisciplinary design optimization

Edward Louis[1], Ahmed Bayoumy[2], Michael Kokkolaras[1]
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1. Introduction / Objectives

Augmented Lagrangian coordination has been used successfully for solving multidisciplinary design optimization (MDO) problems by means of a distributed individual discipline feasible (IDF) approach. The latter must be used in lieu of a multidisciplinary feasible (MDF) approach when the multidisciplinary analysis (MDA) does not converge. In addition, contrary to the MDF approach, the distributed IDF approach offers the ability to use different optimization algorithms for the individual disciplinary subproblems and invaluable insight to the coupling

behavior of the MDO problem. The Lagrangian coordination is based on the alternating method of multipliers, whose updating scheme includes two hyperparameters whose values are selected a-priori based on empirical studies and held fixed during the MDO process . The research presented here uses machine learning (ML) to learn from convergence behavior during early MDO iterations so that these hyperparameters, as well as subproblem optimization algorithm and computational budget, can be adapted dynamically during later MDO iterations to accelerate convergence.

2. Methodology

Learning is enabled by an ensemble of recurrent neural networks. We use a hierarchical sequence modeling approach for anomaly prediction algorithm (see schematic in Figure 1) due to data structure: in the presence of multiple levels of nesting or abstraction, insights about coordination behavior can be extracted from the individual subproblems . An ensemble of RNNs is implemented to forecast coordination behavior because of their effectiveness in predicting anomalies in time-series data . Accurately predicting "spikes" in the convergence history (*cf*. Figure 2) allows for dynamic updates of the coordination hyperparameters to encourage design space exploration when it is predicted to benefit consistency convergence. Dynamic updates are made via a rule-based system, where a predicted spike is encouraged to occur or discouraged from occurring. In cases where no spike is predicted but it is desired, it can be created. When a spike is predicted and desired, design space exploration is encouraged by changing hyperparameter values, subproblem optimization algorithms, and/or subproblem computational budgets.

3. Results / Conclusions

Preliminary comparisons of convergence plots obtained using "static" and dynamic (i.e., learning-based) coordination show promising results. By adapting hyperparameter values, changing subproblem algorithms, and dynamic allocation of computational budgets, improvements in both convergence rate and solution quality are observed. Figure 2 compares the convergence histories obtained by solving the supersonic business jet (SBJ) distributed MDO (DMDO) problem reported in . A dynamic update from iteration 9 to iteration14 based on learning from iteration 1 to iteration 5 results in 34% fewer iterations and shows a 14% improvement in solution quality when the required consistency (q) tolerance is 10^{-10}. Variants of the MADS algorithm are used to solve the subproblems.

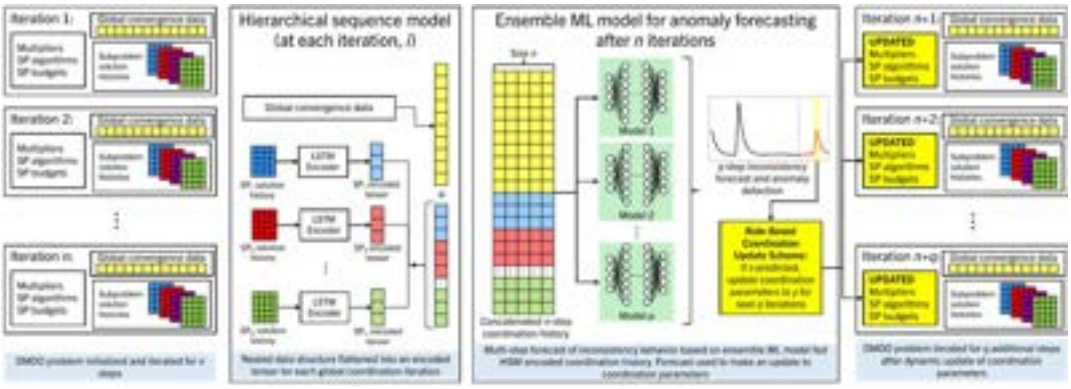


Figure 1. *Schematic of dynamic learning-based coordination of distributed MDO (DMDO) problems.*

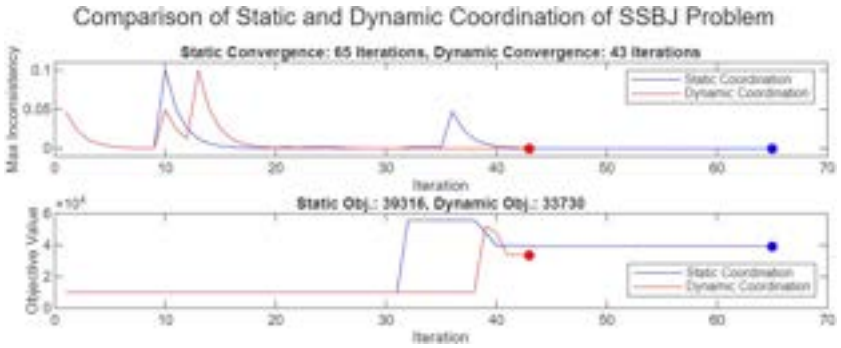


Figure 2. *Comparison of "static" and dynamic coordination for the SBJ MDO benchmark problem.*

Detecting Critical Transitions in Aerospace Technology Systems Using Empirical Dynamic Modeling

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1. Introduction / Objectives

Technological transitions in aerospace systems are often treated as linear processes driven by incremental innovation; however, historical evidence suggests that aerospace development exhibits nonlinear dynamics characterized by abrupt regime shifts, periods of instability, and cascading interactions among technologies, infrastructures, and socio-economic drivers. Inspired by recent advances in ecological resilience theory and empirical dynamic modeling (EDM), this study recontextualizes frameworks originally developed for detecting critical transitions in ecosystems to investigate long-term technological transformations in aerospace systems. In particular, we adapt concepts such as critical slowing down, increasing autocorrelation, variance amplification, and convergent cross mapping (CCM) to analyze transitions between dominant aerospace paradigms, including shifts from propeller-based aviation to jet propulsion, from analog to digital avionics, and from conventional aerospace architectures toward autonomous, sustainable, and AI-enabled systems. The objective is to develop a dynamic causality framework capable of identifying early warning signals of technological regime shifts and reconstructing causal interaction networks among aerospace technologies over extended historical timescales.

2. Methodology

The study combines nonlinear time-series analysis, machine learning, and empirical dynamic modeling (EDM) to investigate aerospace technological evolution as a complex adaptive system. A longitudinal dataset was constructed from historical aerospace technology indicators spanning multiple decades, including propulsion technologies, avionics systems, automation levels, computational capacity, fuel efficiency, safety performance, patent activity, and sustainability-related innovations. Additional exogenous variables such as fuel prices, climate regulations, geopolitical shocks, and public R&D investments were incorporated to account for external forcing effects.

The analytical framework is based on the hypothesis that aerospace innovation trajectories

exhibit nonlinear transitions analogous to ecological regime shifts. To detect such transitions, rolling-window statistical indicators were computed, including lag-1 autocorrelation (AR(1)), rolling variance, and recovery-rate proxies associated with critical slowing down. Increasing autocorrelation and variance were interpreted as potential early warning signals of destabilization preceding technological transitions.
A synthetic dynamical model was implemented in Python to simulate interactions among aerospace technologies under varying environmental and policy conditions. The model integrates positive feedback mechanisms (e.g., network effects and technological adoption), buffering mechanisms (e.g., redundancy and modularity), and destabilizing pressures (e.g., operational complexity or regulatory constraints). Random Forest models were subsequently trained to predict future system states and evaluate "what-if" scenarios involving hypothetical technological interventions, such as the introduction of autonomous flight systems or hydrogen propulsion infrastructures.
To investigate causality beyond simple correlation, Empirical Dynamic Modeling (EDM) and Convergent Cross Mapping (CCM) were applied to reconstruct causal interaction networks among technological variables. Following the framework proposed by Sugihara et al., CCM was used to distinguish true causal interactions from spurious correlations generated by common external drivers. The reconstructed network was analyzed to classify interaction structures into bidirectional coupling regimes, unidirectional forcing regimes, and externally forced non-coupled configurations.
Finally, dynamic network evolution was evaluated through time-varying S-map coefficients and rolling CCM convergence metrics to identify periods of structural reorganization associated with major aerospace technological transitions.

3. Results / Conclusions

The proposed framework demonstrates that aerospace technological evolution exhibits measurable signatures of nonlinear critical transitions comparable to those observed in ecological systems. Early warning indicators, including rising autocorrelation and variance, consistently emerged prior to major technological regime shifts, particularly during transitions involving jet propulsion, digital avionics, and autonomous aerospace systems. CCM analysis successfully distinguished direct technological interactions from variables responding to shared external forcing, enabling reconstruction of dynamic causal networks among aerospace technologies.
The results suggest that aerospace innovation ecosystems may undergo periods of reduced resilience before abrupt reorganization, implying that critical transitions in technological systems can potentially be anticipated rather than observed retrospectively. The integration of EDM, machine learning, and causal network reconstruction offers a novel framework for strategic forecasting, technology policy assessment, and resilience analysis in aerospace engineering. More broadly, this work demonstrates the applicability of ecological complexity frameworks to the study of long-term technological evolution in engineered systems.

The Value of First-Order Relationships in Decision-Making Process

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[3]King's Queue Design, USA

1. Introduction / Objectives

The decision-making process during product development expands throughout the entire duration of its design and manufacturing. Every decision has an effect downstream into the overall process, but often, upstream as well. This translates into unnecessary iterations and results in increased lead time and overall cost of the product development, or indeed the manufacturing of the product.
We argue that the formulation of simple first-order relationships between technical variables and properties of the product and/or manufacturing processes can facilitate quick decision iterations that result in reduced number of iterations between actual decision gates. This capability can bring benefits to reducing the lead time, the cost, and the risk in the process, but also the simplification of decisions at the operational level of the product or service. Another benefit is the strengthening of the communication and understanding between stakeholders and engineering experts. This further triggers discussions about important aspects between experts of different domains which otherwise might be overlooked. The concept is demonstrated through two case studies in Aerospace and Healthcare.

2. Methodology

We demonstrate two ways in developing such first-order relationships. In the first, we deploy the concept of Value Assessment , and as it was extended towards computational engineering design approaches . In the second, we deploy Parallel Coordinates as the means to visualise multi-dimensional data and to discover patterns and relationships by interactive analysis.
The first set of relationships originated from the performance of Change Propagation analysis and the interpretation of the results. The intention is not to have an accurate relationship but sufficient means to advance the understanding and communication within the system in question. Given that this type of analysis is contextual, the relationships can be interpreted in multiple ways as well. The metrics were Design Process Efficiency, or Resilience, and Development Process Efficiency, or Lead Time. The effectiveness of these metrics was demonstrated for the assessment and comparison of architectural concepts of an aeroengine component when considering multiple domains simultaneously.
The Resilience is estimated by considering the number of affected components, so the less yellow boxes and the smaller the number of boxes that appear in the output combined risk matrix the higher the resilience. For the quantification of LeadTime we consider the number of propagation multipliers and the components that are highly linked, and hence, can potentially express a longer design time of these particular components with a negative impart to the overall lead time (Figure 1).
The second set of relationships produced after the analysis of multidimensional data produced from multi-physics simulations of the effectiveness of nanoparticles for cancer therapy . In this example, and as shown in Figure 2, the relationships were discovered thanks

to one of the fundamental properties of Parallel Coordinates, the point-line duality with respect to the Cartesian coordinate system.

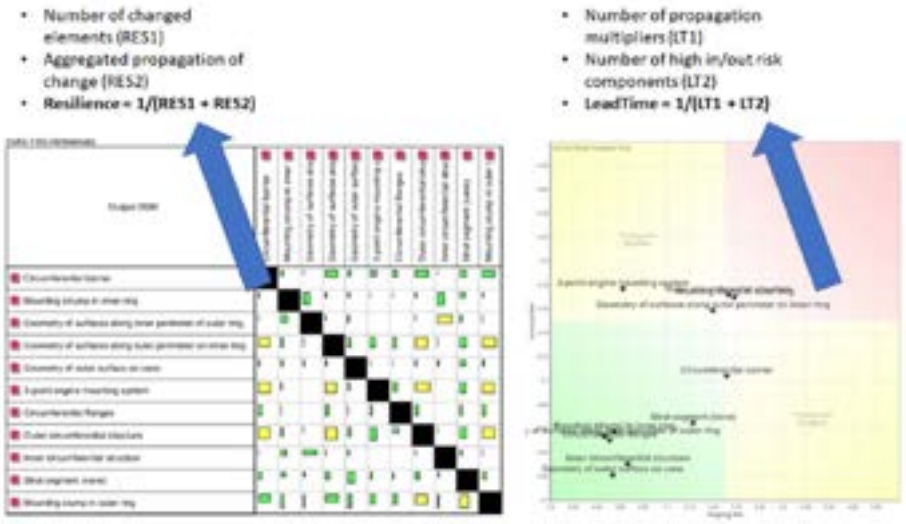


Figure 1. *The output combined risk matrix (left) and the risk portfolio plot (right) from a Change Propagation simulation. The definitions of Resilience and Lead Time are also shown.*

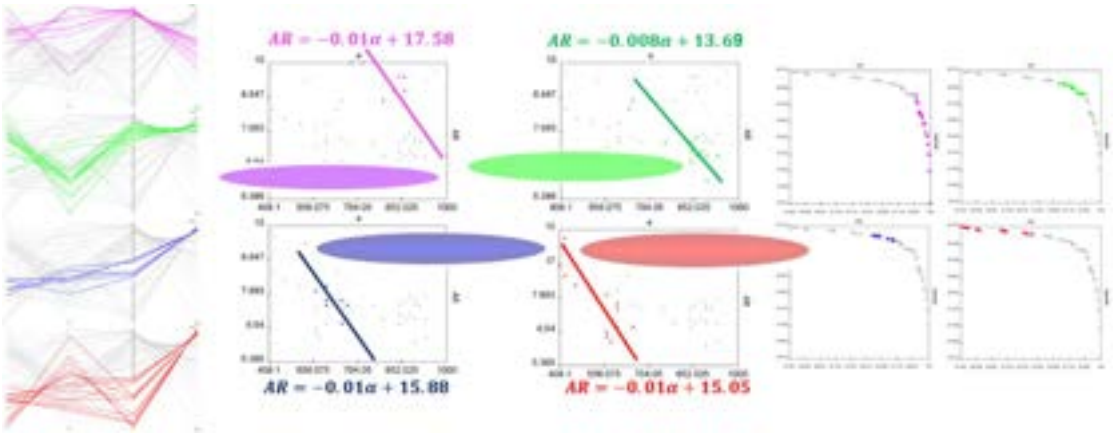


Figure 2. *The discovered relationship between a and AR along the trade-off surface of eta and lambda.*

In a recent study, EXPEED , we have explored the usefulness of combining different modelling approaches to address complementarity and further explore the benefits of such first-order relationships to advance understanding and communication in complex systems design.

3. Results / Conclusions

The benefits of the approach were two-fold. Firstly, to enable assessment of architectural options at the pre-embodiment stage of the product development. This is to facilitate first order decision making and comparison of architectures. Secondly, to reduce the time required in the decision-making process and cancer treatment planning from hours into minutes providing simplification of the process without introducing an error or inaccuracies. In addition, some learnings from the EXPEED study reinforce the construction of such

relationships which can offer a structured way to formulate complex problems and exploit the synergies between different systems modelling approaches, which they can be sanity checked.

Data-Driven Engineering Design for Aerospace Manufacturing and Systems: Promise vs. Perils

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[2]The Pennsylvania State University, USA

1. Introduction

There is no shortage of data when it comes to aerospace manufacturing and systems. The sheer amount of data needed to qualify manufacturing processes and certify components for aerospace systems is overwhelming in its own right, yet it pales in comparison to the amount of data that can be generated during the engineering design and analysis portion of systems development. Meanwhile, both of these can be overshadowed by the test data that is needed to verify and validate components, subsystems, and systems before their flight or launch. While data-driven approaches to engineering design for aerospace manufacturing and systems provide considerable promise for aerospace systems development (e.g., better informed decisions, reduced design iterations, cost and schedule benefits), the reality is fraught with numerous challenges–many of which are not technical in nature. In this presentation, we will discuss the promises of data-driven engineering design, grounding them in the perils that will emerge when transforming organizational practices rooted in paper-based approaches of the past.

2. Methodology

The engineering design community has been developing "data-driven" approaches to support product design and systems development for decades. Several articles have reviewed the breadth and depth of the research to date (e.g.,), and entire books (e.g.,) and dissertations (e.g.,) have been written on the subject. While this list is by no means exhaustive, these reviews underscore the challenges of using data during product design and systems development while highlighting the need to constrain and narrow the scope of any effort to make a contribution. For instance, is the data going to help address customer needs better or make better tradeoffs among competing objectives? Is the data going to improve analysis and simulation models or will the data enable the use of machine learning algorithms to create new simulation models or find optimal designs? Will the data enable better (or faster) decisions? The list goes on, and there is no shortage of future research to be done.

While many of the technical challenges associated with data-driven engineering design have been (or can be) overcome, few have recognized or discussed the challenges and implications of implementing these approaches within an organization, particularly the large organizations that are behind most aerospace manufacturing and systems. Many of these organizations existed long before computers were even invented, and they were organized around paper- and file-based systems that sought to curate the requirements documents,

design calculations (done by hand), experimental results, test reports, field data, and memos (and later faxes) that were generated during systems development. Granted, newer aerospace companies and start-ups can dictate what software, product lifecycle management, and enterprise resource planning tools are used to streamline this, but they need to produce the same qualification data and pass the same certification regulations as any other firm.
Toward this end, we conducted post-mortem reviews of several internal research and development (IRAD) projects focused on enabling data-driven engineering design within a large aerospace organization. IRAD projects varied in duration from 3-months to 18-months and engaged participants with varying degrees of experience from many functional domains, including mechanical engineering, electrical engineering, design and analysis, manufacturing, assembly, testing, and quality assurance. The IRAD projects leveraged ongoing projects to assess user needs and digital technologies that could support data-driven approaches to systems development while using past projects as benchmarks to measure performance improvements or estimate cost and time savings. Sample results follow.

3. Summary of Results

As is common in most large organizations that were designed around paper-based processes, several existing processes are siloed by organizational structure and conducted sequentially (e.g., design→analysis→build→test). As such, data-driven approaches can quickly become mired in organizational challenges related to data access, security, and sharing. It was clear that including disciplines commonly associated with downstream processes (such as manufacturing, quality assurance, and testing) upstream in the systems development process could yield benefits, but people are often hesitant to share data with others outside of their organizational unit. Organizational units consist of groups of people with varying perspectives, backgrounds, and experiences' replacing them with a software tool that synthesizes their data and collective knowledge is an impossible task. Finally, data can quickly overwhelm people; dashboards may help, but they too restrict how much data is available to the viewer.

Structured framework for innovative aircraft design with probabilistic solution spaces using Bayesian networks and the Advanced Morphological Approach

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[2]Russian Academy of Sciences, Russia,

1. Introduction / Objectives

In order to fulfill the political, societal and environmental requirements, the aviation sector currently reaches the decision point on multiple matters – the consideration of novel aircraft configurations, the selection of potentially new energy sources, technology selection for evolutionary development, etc. . The general expectation is such decisions to be made and implemented within a very short timeline by 2050. This requires not only the accelerated

development, but also fast and reliable technology selection and modeling while lacking test data for disruptive concepts.

2. Methodology

This work presents the Framework for the Advanced Morphological Approach (FAMA) as an integrated design methodology allowing the holistic consideration of creative approaches, aircraft design methods, as well as probabilistic philosophy for an increased design reliability under high uncertainties. The FAMA offers a structured workflow with defined steps to identify the relevant technologies and evaluation criteria, to model the system for the selected use case and to generate design solutions aiming to go beyond the designers' experience with the Advanced Morphological Approach . Previous work demonstrated the FAMA application on use cases involving the qualitative identification and evaluation of aircraft design and operational concepts through expert evaluations, different system views and concept selection. This work shows the FAMA use in a more detailed design perspective for the probabilistic estimation of design parameters as well as global figures of merit (FoMs) for the overall aircraft design. In this context, the system modeling is implemented in a semi-quantitative way with Bayesian networks (BNs), which allows the propagation of the uncertainties through the whole system and thus yields a more reliable assessment of uncertain concepts. The focus of the presentation lies in the leveraging of the advantages BNs for the modeling and comparison of highly uncertain designs and their deterministic design parameters . The BNs allow for a balanced combination of limited simulation data with subjective technology estimations and thus yield designs with higher success probability. The methodology is demonstrated on the combination of different promising concepts aiming to reduce induced drag – the strut-braced high-aspect wing, folding wingtips and folding wingtips for a mid-range passenger aircraft. In particular, different types of BN architectures are presented and discussed for different use case types in aircraft design. The approach is enhanced with other machine learning (ML) approaches such as regression trees in the probabilistic context of the BN architectures. The consideration of constraints is ensured by empirical estimations as well as higher fidelity approaches such as finite-elements method (FEM).

3. Results / Conclusions

The semi-quantitative probabilistic FAMA yields a probabilistic solution space which visualizes the FoMs of the different concepts and for varying design parameters. This approach not only helps to compare the solutions but also to diagnose the system modeling and the design sensitivities, as well as to analyze the overlapping design uncertainties. The solution variations are verified against changing design parameters such as wing span, as well as known reference designs from literature. The developed methodology allows to go beyond simulated datapoints by generating original ideas, extending the solution space, and increasing their reliability for a more informed decision-making.

Adaptive Production Planning in Aerospace Manufacturing through the Integration of Knowledge Graphs, Simulations and Cyber-Physical Systems

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1. Introduction / Objectives

Aerospace manufacturing is facing major challenges driven by increasing product complexity, high product variability, fragile global supply chains, and the introduction of climate-neutral technologies such as electric propulsion and liquid hydrogen systems. At the same time, ramping up production rates remains costly and difficult. Conventional production planning and control approaches are often unable to adequately handle the resulting complexity and dynamic changes in production environments.

Three technological approaches are particularly relevant for addressing these challenges: simulation-driven production planning, semantic integration through knowledge graphs, and cyber-physical systems (CPS) in the context of Industry 4.0. Integrating these technologies into a closed-loop architecture, in which live shop-floor data continuously updates a semantic representation of the production environment used for simulation-driven replanning, enables more adaptive and resilient aerospace manufacturing systems capable of reacting to disruptions, changing resource availability, and production variability during ongoing operations (Wan et al. 2024).

Therefore, this work presents a methodology for integrating simulations, knowledge graphs, and cyber-physical systems into a closed feedback loop enabling adaptive production planning and control in aerospace manufacturing. The proposed approach aims to improve robustness, flexibility, and responsiveness to disruptions and changing production conditions.

2. Methodology

The proposed methodology combines cyber-physical systems, knowledge graphs, and simulation-based optimization into a unified adaptive production framework.

Simulation-driven production planning enables the identification of bottlenecks, process dependencies, and critical resource constraints during the planning phase. However, production simulations are typically based on assumptions that increasingly diverge from real production conditions over time. Consequently, static simulation models become less reliable during ongoing operations.

Knowledge graphs provide a semantic framework for integrating heterogeneous information domains across the product lifecycle. In the manufacturing context, they enable the structured linkage of product, process, and resource information from a variety of data sources while making dependencies and relationships between production elements more transparent. This, furthermore, enables the application of knowledge-based engineering methodologies to derive further information from the linked data. Nevertheless, the full potential of these semantic models requires continuous enrichment with operational production data and advanced analytical methods.

Cyber-physical systems enable the continuous acquisition of production data and the networking of manufacturing systems in real time. Machine states, process durations, and production progress can thereby be monitored continuously. However, without suitable mechanisms for semantic interpretation and adaptive decision-making, the value of these data streams remains limited.

The proposed approach connects the shop-floor level to a semantic knowledge graph through cyber-physical systems continuously acquiring live production data. Based on this updated representation of the production environment, simulation tools are used to dynamically re-plan and optimize ongoing manufacturing operations. The resulting optimized production plan is subsequently executed through the cyber-physical production system, thereby creating a closed adaptive feedback loop. Figure 1 illustrates the information flow and feedback mechanisms between the production system, knowledge graph, and simulation environment.
The methodology is evaluated using the exemplary production of aircraft cabin monuments. The demonstrator investigates the capability of the proposed framework to adapt production schedules and resource allocations to changing environmental conditions, production delays, and disruptions in real time.

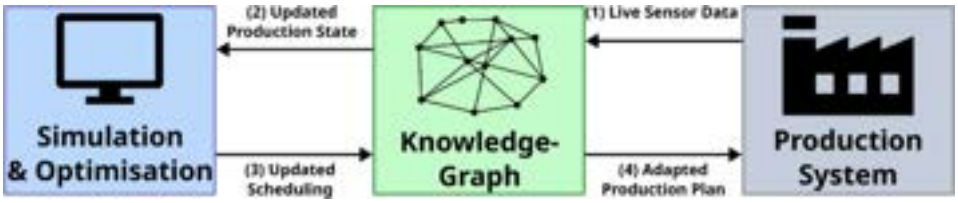


Figure 1. *Schematic Illustration of the proposed method linking simulation, knowledge-graphs and production environments.*

3. Results / Conclusions

The demonstrator demonstrates the capability of the proposed framework to dynamically adapt production schedules and resource allocations in response to disruptions and changing production conditions. By integrating cyber-physical systems, knowledge graphs, and simulation-driven optimization into a unified framework, the approach enables adaptive production planning and control based on actual production conditions and continuously acquired shop-floor data.
The closed feedback loop allows production systems to dynamically react to changes in product configurations, resource availability, and environmental conditions during ongoing operations. This contributes to more robust and flexible aerospace manufacturing processes while supporting competitive and resilient production systems.
The presented work demonstrates an important step toward self-adaptive aerospace production systems capable of continuously aligning planning and execution throughout the manufacturing lifecycle.

Utilising AI and LLM for rigorous uncertainty construction

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1. Introduction / Objectives

Uncertainty quantification plays an increasingly important role in the design, manufacturing, certification and operation of aerospace systems. However, due to the difficulty in tracking

and characterising the uncertainty about the thousands of different quantities, it is regularly replaced by a best-guess value, assigned a convenience distribution, or shifted to a final safety factor.

2. Methodology

The advancement of large language models (LLM) and the artificial intelligence (AI) agents powered by them allows for the processing of large amounts of data and the extraction of semantically sensible insights from it. Retrieval-augmented generation (RAG) has additionally proven to be instrumental in focussing the attention of LLMs to contexts relevant to answering a specific query and is a primary mechanism to reduce hallucinations.

3. Results / Conclusions

We present the concept and first results for a RAG-based uncertainty constructor which combines classical approaches for rigorous processing of evidence with the recent advancements in reliable RAG systems and knowledge graph representations. The constructor system is orchestrated by a provenance-tracking and justification agent, which maintains a rationale trace for the constructed uncertain numbers, allowing engineers to track and reason about the evolution of uncertainty in the design.

Expert-in-the-loop Explainable Artificial Intelligence to Support Design Engineering Decision Making

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1. Introduction / Objectives

In many engineering domains, including aerospace design, gaining insight into complex datasets relies heavily on manual, expert-driven analysis supported by domain heuristics or structured models. Such processes are time-consuming, difficult to scale, and prone to subjectivity when identifying nonlinear relationships between design variables. This work proposes an **XAI-driven knowledge discovery approach** that complements expert reasoning with data-driven insights extracted from predictive models. Rather than replacing expert analysis, the approach integrates automated discovery with prior knowledge: relationships identified from data can be validated or constrained using expert input, while expert-defined dependencies (e.g., known variable couplings) can be systematically assessed against empirical evidence. The objective is to demonstrate how explainable predictive models can support **automatic discovery of relationships and trade-offs**, enabling scalable and interpretable analysis in complex design spaces.

2. Methodology

The proposed approach combines predictive modeling with explainable AI (XAI) to extract

interpretable relationships between design variables. **In this work, we employ an Explainable Boosting Machine (EBM)** due to its ability to explicitly model feature contributions and interactions. However, the approach is not restricted to this choice: **any high-capacity black-box model** (e.g., neural networks or ensemble methods) could serve as the predictive backbone. While such models typically offer only predictive capability, when combined with XAI techniques, they enable **systematic knowledge discovery from learned patterns assuming the XAI forma is aligned with expert preferences.** The model is trained to predict the performance metric **IPS_ACCESSIBILITY** based on geometric parameters from the DIAS dataset.

Because the EBM model is inherently interpretable, the overall IPS_ACCESSIBILITY score is obtained as a sum of these components, meaning that both individual features and their interactions directly influence the prediction. The model achieves F1 score at the level of 92%. Feature interactions are automatically identified during training, enabling discovery without manual specification. Additionally, the approach allows incorporation of **expert-defined relationships**, similarly to dependencies encoded in Bayesian networks, either to guide the analysis or to validate model-discovered patterns. Figure 1 illustrates two interaction effects. The first, between *vane_lean* and *vane_le_radius*, is discovered automatically by the model. The interaction heatmap shows that lower values of both parameters produce positive contributions to IPS_ACCESSIBILITY, while increasing vane_lean results in progressively negative contributions, particularly for larger radii. This indicates a **nonlinear trade-off**, where high vane lean combined with large leading-edge radius degrades accessibility. The second interaction, between *vane_total_count* and *vane_lean*, reflects an **expert-imposed relationship**. The visualization shows a consistent gradient: increasing vane_total_count improves model predictions, particularly for smaller vane_lean values. This confirms alignment between expert expectations and data-driven evidence, demonstrating how the approach supports **joint reasoning between data and domain knowledge**.

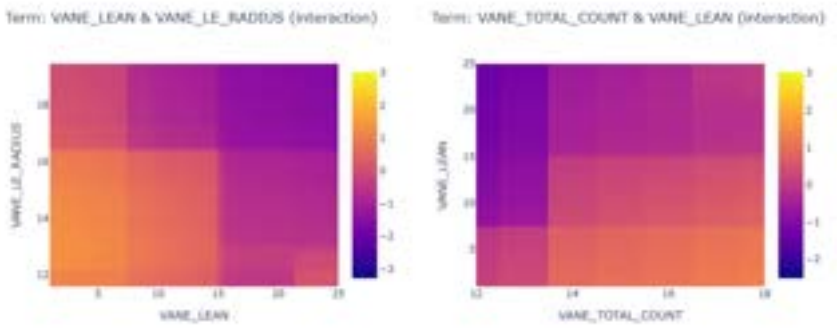


Figure 1. Pairwise interaction contributions $f_{ij}(x_i, x_j)$ in the EBM model predicting *IPS_ACCESSIBILITY*, showing an automatically discovered relationship (*vane_lean* × *vane_le_radius*, left) and an expert-imposed dependency (*vane_total_count* × *vane_lean*, right), where color indicates the additive effect of each configuration on the predicted score.

3. Results / Conclusions

The results demonstrate that explainable predictive models can effectively uncover meaningful relationships between design variables while maintaining high predictive power.

Automatically discovered interactions reveal nontrivial dependencies that would be difficult to identify through manual analysis alone, while expert-defined relationships are preserved and validated within the same framework. The interpretation of EBM interaction terms provides a direct quantitative view of how parameter combinations influence IPS_ACCESSIBILITY, enabling actionable insights for design exploration. Overall, the proposed approach enables **scalable, data-driven knowledge discovery** that complements expert-driven analysis. By combining predictive modeling with explainability, the framework supports both hypothesis generation and validation, offering a practical tool for analyzing complex engineering systems enabling at the same time a predictive power of the machine learning model to be used in other tasks.

Visual Analytics-Enabled Design Space Exploration of Aircraft Configurations from Top-Level Requirements

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1. Introduction / Objectives

Modern aircraft conceptual design requires the rapid exploration of a large number of candidate configurations while satisfying top-level aircraft requirements, operational constraints, and competing performance objectives . At the early design stage, however, decision-making is often hindered by large tabular datasets, many discrete configuration choices, and multiple coupled aircraft-level metrics such as mass, fuel consumption, range, stability, emissions, and cost. Although zero-fidelity and conceptual-level models enable fast evaluation of many design options, the resulting design spaces can still be difficult to interpret, especially when multiple stakeholders must understand trade-offs and agree on a small number of promising configurations for further analysis.

2. Methodology

This work presents a visual analytics-enabled methodology for requirement-driven aircraft design space exploration and multi-objective optimisation using Airbus top-level aircraft requirements as the guiding design criteria. Figure 1 presents the Visual Analytics Framework used in this study. A zero-fidelity aircraft dataset containing 500 candidate design configurations was used to explore the impact of different design and operational choices, including fuel type, additional tank architecture, wing configuration, empennage layout, propulsion option, passenger capacity, and design range. The dataset also includes aircraft-level outputs covering top-level requirements, mass breakdown, mission performance, take-off and landing characteristics, stability indicators, total cost, and CO_2 emissions. These data were used to perform design space exploration and multi-objective decision support, with the aim of identifying attractive configurations that balance performance, feasibility, and operational suitability.

The proposed workflow combines requirement filtering, multi-objective trade-off analysis, and interactive visual analytics. First, the aircraft configurations are assessed against top-level constraints such as passenger requirement, design range, field length limits, maximum wingspan, cruise condition, stability margin, and mission-level performance. Next, relevant

objectives and decision metrics are compared, including gross mass, fuel consumption, CO_2 emissions, total cost, mission distance, and stability behaviour. Instead of analysing individual parameters in isolation, the visual analytics environment enables designers to examine the full multi-dimensional design space through linked plots, ranked design tables, scatter plots, parallel-coordinate views, and configurable filtering. This allows engineers to identify dominant trends, remove infeasible or unattractive configurations, compare competing technologies, and understand the consequences of each design choice.

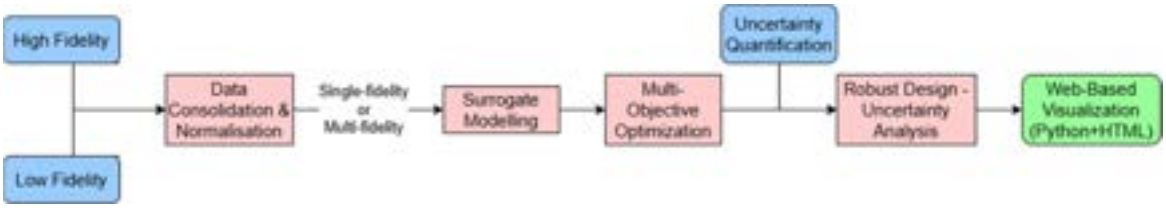


Figure 1. *Multi-Fidelity Visual Analytics Framework for Design Space Exploration.*

3. Results / Conclusions

The methodology was applied to shortlist three promising aircraft design configurations from the full set of 500 candidates. The down-selected configurations represent different trade-offs between aircraft size, range capability, fuel/energy option, system architecture, performance, cost, and emissions. The visual analytics approach supports transparent justification of the down-selection process by showing why certain configurations are preferred and why others are rejected, particularly valuable in early-stage aircraft design. This work extends conventional conceptual aircraft design studies by combining zero-fidelity aircraft-level data, requirement-based filtering, multi-objective design space exploration, and interactive visual analytics into a single decision-support workflow. The framework enables fast interpretation of large configuration datasets, supports collaborative design reviews, and provides a practical bridge between early conceptual studies and later higher-fidelity analysis. Ultimately, the approach helps engineering teams move from hundreds of possible aircraft concepts to a small number of justified candidate configurations for further multidisciplinary refinement, higher-fidelity simulation, and technology assessment.

How Much Autonomy Should an Engineering Agent Have? Benchmarking LLM Harnesses for Airworthiness Verification

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1. Introduction / Objectives

Large Language Model (LLM) agents have matured enough to support engineers in engineering analysis tasks, including airworthiness-related ones [1, 2]. With an appropriate division of roles, agents operate alongside the validated CAE and programming tools engineers already trust, rather than replacing them [3]. Regulators acknowledge this shift: the

EASA AI Concept Paper does not exclude AI from certification activities, but frames their use as a matter of managed risk [4]. Yet the performance of an agent cannot be guaranteed, because the underlying LLM is stochastic. Several agentic harness techniques exist to constrain and structure this behaviour, but how they trade engineering performance against the effort to implement and maintain them (and against the residual risk that must ultimately be certified) remains unexplored. This work aims to quantify that trade-off, providing the metrics needed to judge which agentic implementations are cheap and robust enough for engineering verification.

2. Methodology

The study proceeds in three steps. First, we review the engineering and agentic literature to identify the harness techniques currently used to deploy LLM agents in technical workflows, and we organise them along an axis of increasing autonomy, e.g. how much freedom the agent is given to decide and act. We position these techniques against the EASA AI Concept Paper so that the comparison speaks to the risk categories relevant for future certification.

Second, we fix a single reference engineering process and re-implement it under each harness. The reference is the mechanical finite-element strength evaluation used in [1]: an aerospace structural component whose loads must be processed and verified following a documented design practice. Holding the engineering task constant isolates the effect of the harness.

The harnesses span the autonomy spectrum: (i) a deterministic graph orchestration (implemented with Pydantic AI [5]), where the control flow is fixed and the LLM only fills predefined nodes; (ii) a constrained **tool-calling** agent exposed to domain tools through the **Model Context Protocol** (MCP) [6]; (iii) a **code-mode** agent that writes and executes its own tool-calling code [7]; and (iv) a **fully autonomous** coding agent with file-system and shell access (Claude Code [8]). Across (i)–(iv) the agent is granted progressively more freedom to choose its actions. We additionally vary the backing model size to expose the cost–capability frontier.

Third, we evaluate each configuration on the same task and expert-defined acceptance criteria, repeating runs to capture the stochastic spread. Primary metrics are correctness against ground truth, wall-clock time, and token cost (a proxy for model size and therefore GPU/compute requirements) complemented by the implementation and maintenance effort each harness demands. Read together, these metrics let us locate the configurations where engineering risk is acceptably low at the lowest cost.

3. Results / Conclusions

This is ongoing work; results will be presented at the conference. We expect the harnesses to trace a clear autonomy–robustness frontier: the more constrained harnesses (graph, tool-calling) should be cheaper to run and easier to certify, but brittle when inputs deviate from the documented practice, while the more autonomous harnesses (code-mode, fully autonomous) should absorb that variability at the price of higher token cost, longer run times, and a larger residual risk to supervise. Crossing this against model size, we anticipate sweet spots: harness-and-model combinations that maximise correctness while minimising compute (and therefore GPU/cost) , rather than a single dominant configuration. The intended impact is a practical, EASA-aligned basis for choosing how much freedom to grant an engineering agent: instead of asking whether AI is admissible in verification, engineers and certification

bodies gain measured metrics to decide which implementation keeps the residual risk acceptably low at an acceptable cost.

BEYOND VISUALIZATION: EXPLAINABLE AI FOR COMPLEX DATA EXPLORATION

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1. Introduction

Modern conceptual aircraft design increasingly relies on large-scale simulations and Design of Experiments (DoE), generating vast datasets that complicate the extraction of meaningful insights. While platforms like DIANA provide detailed individual data point insights and visualizations, efficiently analyzing and navigating these high-dimensional spaces remains a significant challenge. In such cases, it is crucial to identify key configurations worthy of further in-depth analysis and justify this selection through transparent, interpretable criteria. This paper proposes a unified framework integrating multidimensional visualization, automated data analysis, and Explainable Artificial Intelligence (XAI). Following a state-of-the-art review, the implementation within our data platform is presented. The methodology is validated using benchmark datasets and subsequently applied to an aircraft engine health data set to identify critical operational states and failure modes. Results demonstrate the framework's versatility in reducing large design and operational spaces to smaller, well-justified subsets of significant candidates for detailed analysis and informed engineering decisions.

2. Methodology

Modern engineering relies on data analysis techniques to extract insights from extensive datasets and identify significant configurations. However, these methods often lack inherent explainability, creating a gap between automated results and human understanding. To address this, we propose a unified framework that integrates analytical tools with Explainable AI (XAI) and interactive visualization, ensuring the analysis process is both transparent and interpretable. This approach allows engineers to navigate high-dimensional spaces while understanding the underlying rationale behind each identified point.

The methodology is structured into a multi-stage pipeline. First, surrogate models are leveraged to identify the most significant variables, enabling the dimensionality reduction required for efficient analysis. Subsequently, three specialized analysis modules can be performed: outlier detection to identify anomalous states, automatic clustering to group data patterns, and Pareto front identification to isolate optimal trade-offs. Finally, results and their interpretations are presented through an interactive report featuring multidimensional charts.

In the technical implementation, CatBoost is employed to construct the surrogate models, while Accumulated Local Effects (ALE) are utilized to map input influences and handle correlated variables. This interpreted space serves as the foundation for the core modules:

- Outlier Detection: Anomalies are identified using KNN (to detect local density deviations) and ECOD (to capture global distribution tails). The resulting outlierness

score is analyzed via SHAP to identify the variables driving the anomaly, visualized through waterfall (local) and beeswarm (global) plots.

- Automatic Clustering: Hidden structures are identified using K-Means (or K-Prototypes). The most influential variables are obtained through Mutual Information, with results presented via interactive 3D scatters and box plots showing centroids and medoids as the most representative points of these structures.
- Pareto Fronts: Optimized trade-off solutions are explored through interactive tools, including parallel coordinates and colored Pareto fronts, among other specialized charts. Mutual Information is again leveraged to highlight the most promising variables.

To ensure reliability, the framework provides key validation metrics, such as R2 scores for surrogate accuracy and Silhouette coefficients for clustering quality, plus additional statistical indicators. This integrated workflow ensures that the final engineering selection is not only optimal but fully justifiable and statistically sound.

3. Results / Conclusions

The framework was validated using benchmark datasets, achieving an F1-score of 0.95 on the Wine dataset for clustering and 0.88 on the Breast Cancer dataset for outlier detection, with XAI results aligning with established literature. For the aerospace application, the NASA C-MAPSS FD003 dataset was utilized. Starting with feature selection through surrogate modeling, computational overhead was reduced and synthetic noise eliminated. Subsequently, the automatic clustering successfully identified distinct operating modes, providing explanations consistent with expected physical behavior. Finally, outlier detection isolated critical engine states with local sensor-level interpretations. These results demonstrate that the framework effectively filters high-dimensional datasets to highlight the most significant data points and hidden structures. By automating the process and providing interpretable insights, it enables engineers to bypass exhaustive manual searches and focus directly on the most relevant configurations, streamlining the path from massive data collection to specialized, high-level engineering analysis.

On AI-Enabled Quality-Oriented Manufacturing Process Steering

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National Technical University of Athens, Greece

1. Introduction / Objectives

Adaptive manufacturing requires not only process monitoring, but also mechanisms for translating predicted quality deviations into corrective actions. This work presents an AI-enabled process feedback methodology for quality-oriented steering in manufacturing operations, demonstrated through a CNC turning use case. The objective is to close the loop between sensor-based process monitoring, virtual-environment-based policy training, and corrective feedback to either the machine or the human operator. Building on prior work in raw-signal process monitoring and local digital infrastructure for legacy CNC machine tools , the proposed approach introduces a reusable architecture in which monitored process state

is converted into process control parameter corrective recommendations, in this case: feed and spindle override. The main innovation lies in combining synthetic-signal-enabled virtual interaction, reinforcement-learning-based steering, and dual feedback delivery through both a Human-Machine Interface (HMI) and a Machine-Integration API.

2. Methodology

The proposed methodology follows a process-causality-chain view of manufacturing operations, where controllable process parameters and fixed setup conditions generate measurable process side-effects, which in turn determine quality metrics. In the general formulation, a process monitoring model estimates the current quality state from sensor streams, while a steering model uses this information to determine corrective actions on available process levers, i.e. controllable parameters. The methodology is process-independent: for a new manufacturing operation, the measured side-effects, quality metrics, controllable parameters, and operating constraints are redefined, while the monitoring–steering–feedback structure remains unchanged.

The workflow was demonstrated on a CNC turning process, where the monitoring layer uses synchronized vibration, speed, and torque-related signals to predict surface roughness and dimensional deviation classes. The steering observation combines compact signal-derived features, monitoring-model class probabilities, recent process history, and previous corrective actions. Corrective actions are defined as discrete feed and spindle override commands, expressed as ‘decrease’, ‘hold’, or ‘increase’ operations, making the controller compatible with both operator-mediated decision support (HMI) and automatic actuation (API).

Since direct experience-based learning on physical equipment is costly and potentially unsafe, model training is performed in a virtual environment supported by synthetic signal generation via conditional Generative Adversarial Networks. The environment maintains hidden process state, generates realistic signal windows, applies the monitoring model, evaluates the process reward, and exposes only deployable observations to the steering policy. The training workflow, shown in Figure 1, consists of two stages. First, a privileged teacher uses simulator access to evaluate locally favourable actions and generate labelled state–action examples. A student policy is then trained from these examples. Second, the student policy is refined using reinforcement learning , specifically Proximal Policy Optimization , to improve closed-loop behaviour under repeated interaction. The reward promotes high confidence in the desired roughness class, activates productivity reward only when quality is acceptable, penalizes unnecessary control movement, and incorporates process-specific operating limits.

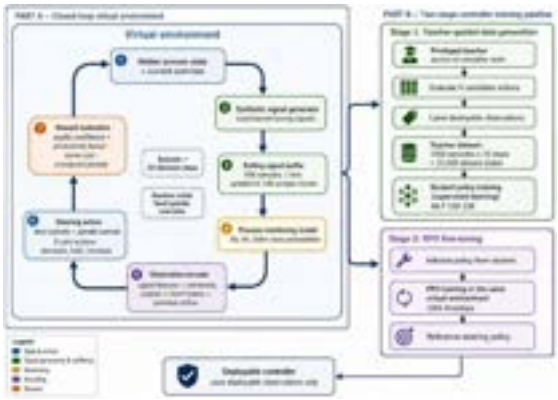


Figure 1. *Process steering training workflow: A) closed-loop virtual environment; B) two-stage training pipeline.*

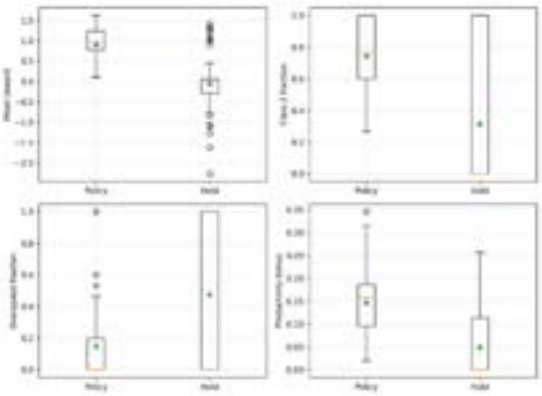


Figure 2. *Aggregate policy-versus-hold metrics over randomized closed-loop turning episodes.*

3. Results / Conclusions

The trained steering policy was evaluated against a 'hold' reference policy, that corresponds to passive monitoring without any corrective actions, over randomized closed-loop turning episodes. As shown in Figure 2, the policy improved mean reward from approximately -0.04 to 0.93, increased the target roughness-class fraction from 0.32 to 0.748, reduced overspeed exposure from 0.48 to 0.153, and increased the productivity bonus from 0.051 to 0.149. Non-target quality states were recovered within the rollout horizon, with an average recovery time of approximately 3.3 corrective steps. These results show that the proposed methodology can transform monitoring outputs into meaningful corrective actions while balancing quality, productivity, and process constraints. Although demonstrated through CNC turning, the architecture is applicable to machining processes where suitable process signals, quality metrics, controllable parameters, and synthetic training environments are available.

A data-driven method for smart wind tunnel testing planning

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1. Introduction / Objectives

The current practice of wind-tunnel testing is based on fixed testing matrices sweeping through the full experimental design space. While comprehensive, this approach often results in the acquisition of large volumes of data in regions where the flow is predictable, well-behaved and adequately understood. Consequently, valuable facility time and operational cost are consumed by measurements that offer limited additional insight. This work introduces a machine learning methodology to make wind tunnel campaigns more efficient by focusing the data acquisition on the portions of the aerodynamic response that behave unexpectedly or nonlinearly. By concentrating the new observations in these informative regions, the same level of aerodynamic knowledge could be achieved with fewer experiments, reducing cost and time while improving scientific yield.

2. Methodology

The proposed methodology (presented in Figure 1) combines surrogate modelling, metrics extraction, and probabilistic inference into an active learning framework for wind tunnel testing. The overall framework is implemented as a closed-loop active learning process.

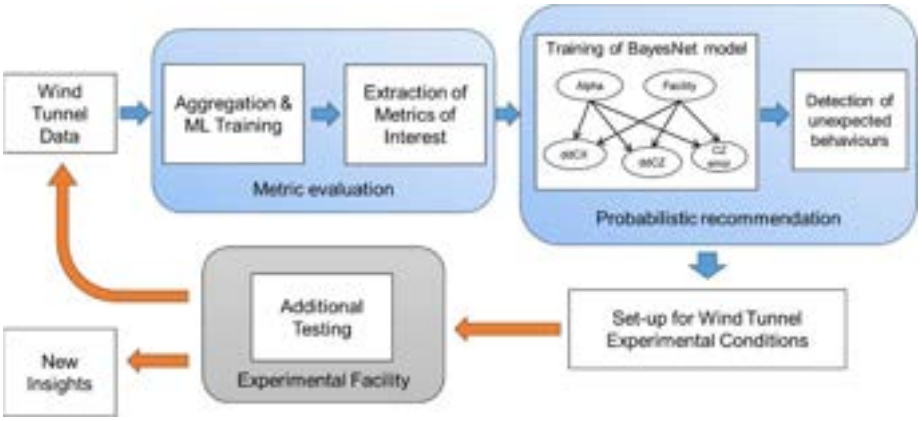


Figure 1. *Developed Methodology for Smart Wind-tunnel testing.*

The wind tunnel data is first aggregated into a continuous differentiable function using Gaussian Processes (GPs) , which enable to quantify the uncertainty due to the sparsity of data and extract curvature-based indicators for the identification of rapid changes in aerodynamic measurements. This information is used to train a Bayesian Network, which connects the metrics to the experimental campaign parameters. At each iteration, the Bayesian Network is queried to determine the next most informative experimental points, typically those exhibiting high joint probability of uncertainty and curvature. New data are then incorporated into the dataset, the model is updated, and the process repeats.
The methodology has been tested using the axial force and normal force coefficients of the SWiFT aerodynamic dataset from ARA by simulating the sequential data acquisition. An initial set of sparse points was used to bootstrap the algorithm, and synthetic data was sampled from the full dataset by introducing Gaussian noise to represent new experimental measurements based on the top three recommendations in angle of attack suggested by the acquisition model. Convergence of the algorithm is evaluated by comparing the error between the estimated Gaussian Process function and the true complete dataset at each iteration.

3. Results / Conclusions

The active learning framework demonstrated rapid convergence of aerodynamic predictions while significantly reducing the number of required test points. In the simulated campaign, accurate reconstruction of the aerodynamic response was achieved with up to 44% fewer measurements, with key features such as stall onset being identified early through curvature-based metrics. The axial force coefficient converged particularly quickly due to the clear detection of the stall break, while the normal force coefficient required additional

iterations due to more complex behaviour. Overall, the methodology successfully focused sampling on high-value regions of the design space, improving efficiency without compromising fidelity. These results highlight the potential of combining Gaussian Processes and Bayesian Networks for intelligent test planning, enabling reduced experimental cost, improved utilisation of wind tunnel facilities, and real-time decision support during campaigns. Ultimately, the approach lays the foundation for adaptive, data-driven experimental design tools capable of enhancing both the efficiency and scientific output of future aerodynamic testing programmes.

Interface Design and Digital Twins for Dimensional Control in Composite Assemblies

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Chalmers University of Technology, Sweden

1. Introduction / Objectives

Geometry assurance is a systematic approach for managing geometrical variation and dimensional quality throughout product development and production. It predicts, controls, and reduces effects of uncertainty from part manufacturing, fixture systems, assembly sequences, and joining processes. This is particularly important for composite assemblies, where flexible components may be sensitive to stress, bending, and deformation during assembly. Interface mismatches and geometric variation can generate assembly-induced stresses that may damage components and cause structural defects. In aerospace composite structures, shimming is commonly used to compensate for gaps and interface mismatches, but excessive or poorly controlled shimming may increase cost, assembly complexity, and reduce structural performance. The objective of this work is to present a design method for nominal interface design supporting improved dimensional accuracy and optimized shimming, and to show how non-rigid variation simulation models can be reused as digital twins for individual assembly adjustments in production.

2. Methodology

To make the simulation computationally efficient, the Method of Influence Coefficients is used together with finite element-based sensitivity matrices. This enables prediction of assembly deviations, gaps, contact forces, and stress responses for a large number of variation cases without running a full finite element analysis in every iteration. For composite components, assembly-induced stresses are evaluated using a composite failure criterion, such as the Tsai–Hill criterion, to identify critical locations and assess whether geometric variation and interface mismatches may lead to unacceptable stress levels.
Based on these simulations, the proposed nominal interface design method evaluates how interface geometry influences gaps, shimming needs, stress levels, and final dimensional quality. Alternative nominal interface designs can thereby be compared with respect to robustness, shim thickness distribution, and sensitivity to part and fixture variation. The aim is to support early design decisions that reduce the need for excessive shimming while maintaining dimensional accuracy and structural performance.
The same simulation model can also be reused during production as a basis for a digital twin.

By combining measured data from individual parts or subassemblies with fast variation simulation and optimization, the assembly process can be adjusted for each individual product, for example through adapted locator settings, joining strategies, or additional shimming .

3. Results / Conclusions

The proposed nominal interface design method, illustrated using the wingbox case study in Fig. 1, provides a structured way to balance final geometrical quality against the amount of shimming required in composite assemblies. By evaluating alternative nominal interface geometries through non-rigid variation simulation, the method supports design decisions where deviations from nominal product geometry and shim thickness distributions are considered simultaneously. This enables identification of interface designs that improve dimensional accuracy while avoiding excessive shimming, thereby reducing assembly complexity, added weight, and potential negative effects on structural performance. Furthermore, the reuse of variation simulation models as digital twins in running production shows potential to increase the geometrical quality of assemblies and final products with up to 60%, without tightening tolerances at part level. Instead, quality improvements can be achieved through individual assembly adjustments based on measured part and subassembly data.

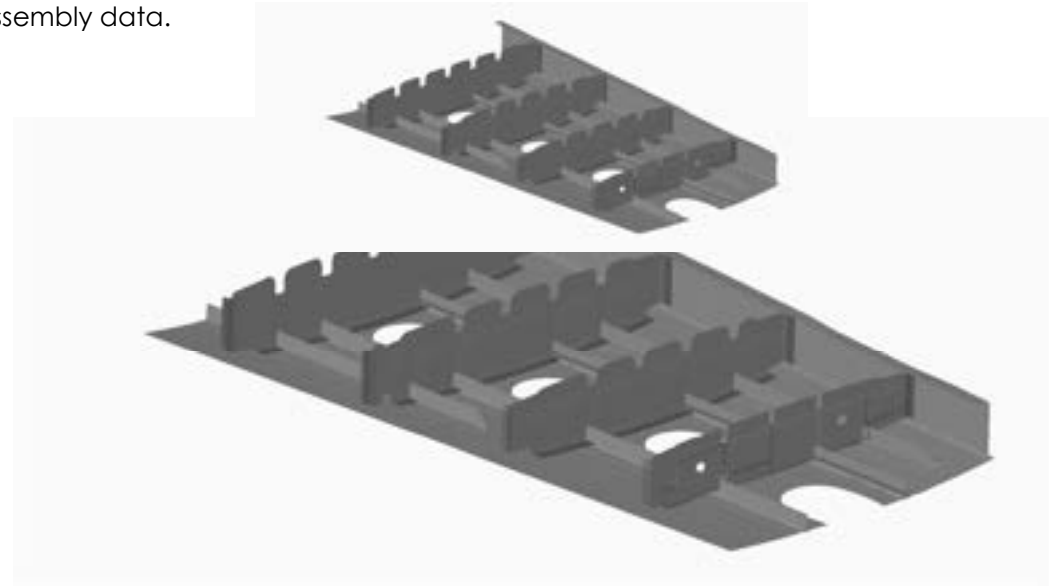


Figure 1. *Wingbox case study for design gap specification.*

Data-driven multiscale modelling of buckling metamaterials for vibration mitigation and protection of airborne electronics

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1. Introduction / Objectives

The continuous integration of advanced avionics, flight-control electronics, and health-

monitoring systems in modern aircraft increases the demand for lightweight solutions capable of protecting sensitive equipment against severe vibration environments. Conventional isolation systems often introduce mass penalties and offer limited adaptability to stringent aerospace requirements. Mechanical metamaterials have emerged as a promising alternative due to their ability to exploit microstructural instabilities and elastic buckling of periodic lattice microstructures to dissipate energy and attenuate dynamic loads . However, designing these materials requires multiscale simulations (FE^2) that suffer from prohibitive computational overhead. This work proposes a data-driven multiscale framework for the efficient modelling of buckling-driven mechanical metamaterials. The objective is to develop a computationally efficient homogenization strategy that preserves the nonlinear energy-dissipation mechanisms arising from microstructural buckling while enabling large-scale structural analyses suitable for aerospace design workflows.

2. Methodology

The proposed framework combines computational homogenization and machine-learning surrogate modelling. At the microscale, periodic lattice unit cells are modeled using beam elements formulated within a small-strain, large-displacement kinematic setting to accurately capture geometric instabilities and elastic buckling . To bypass the computational burden of concurrent FE^2 simulations, a database of homogenized responses is generated to train Gaussian Process (GP) surrogate models. The GP model learns the complex constitutive mapping between the macroscopic strain tensor and the resulting Piola-Kirchhoff stress.
A pivotal advantage of this GP-based formulation is that the algorithmic tangent stiffness matrix can be derived analytically from the surrogate. This ensures gradient consistency and enables the seamless integration of the homogenized microstructural behavior into macroscale implicit finite element solvers, maintaining computational tractability. To maximize data efficiency, an active learning protocol is adopted by monitoring the uncertainty in the posterior distribution of the surrogate function. Consequently, the training dataset is enriched via targeted sampling only in regions of the design space where the model's predictive confidence is lowest, ensuring high global accuracy with minimal data points.

3. Results / Conclusions

The proposed methodology accurately reproduces the nonlinear mechanical response associated with buckling-induced energy dissipation while substantially reducing the computational cost compared with conventional concurrent multiscale simulations. A comparative assessment demonstrates that for this class of nonlinear mechanical problems, Gaussian Processes provide a more robust alternative to traditional artificial neural networks, particularly regarding uncertainty quantification and gradient consistency required for the convergence of macroscale implicit solvers.
From an aerospace perspective, the framework provides an efficient digital design tool for optimizing metamaterial-based vibration isolation concepts. Potential applications include protective enclosures for avionics, vibration mitigation devices for airborne electronic equipment, and lightweight multifunctional structural components with integrated energy-absorption capabilities. In conclusion, this data-driven paradigm bridges advanced material

architectures and aircraft-scale structural simulations through computationally tractable multiscale modelling techniques.

Determination of material model parameters for composite materials for aircraft structural design using machine learning

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1. Introduction / Objectives

The reliable calibration of material models is a key requirement for robust numerical simulations, especially for the application of composite structures in aircraft engineering. Particularly for safety-relevant lightweight structures, nonlinear material behavior, damage mechanisms, and failure-relevant effects must be represented as realistically as possible. However, complex composite material models contain numerous parameters that cannot always be directly determined from experimental material properties and therefore often need to be identified using iterative and time-consuming optimization procedures. The objective of this work is to develop a machine-learning-based inverse approach for the automated prediction of suitable material model parameter sets from real experimental data, supported by systematically generated simulation data. This aims to reduce the calibration effort, enable faster provision of material cards, and accelerate and systematically support virtual design processes for aircraft structures.

2. Methodology

The developed methodology is based on a data-driven workflow for the inverse identification of material parameters for composite material models. As a specific application case, the LS-DYNA composite material model MAT_058 is considered, in which relevant material parameters are systematically varied and used to generate a virtual database. For this purpose, representative virtual tests are set up and simulated using LS-DYNA.

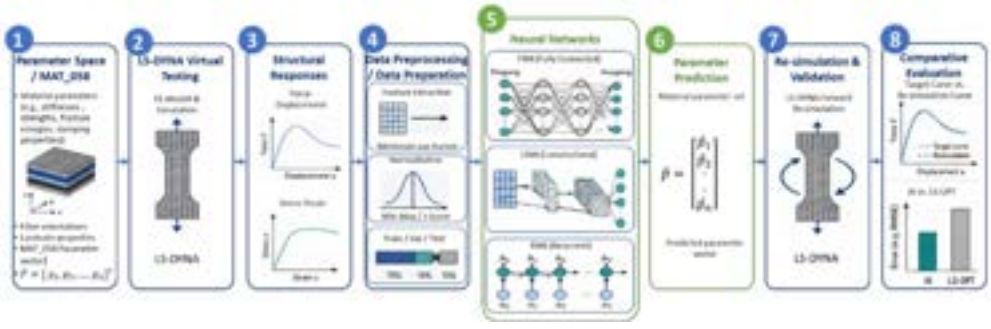


Figure 1. *Workflow of the machine-learning-based inverse material parameter identification for composite material models.*

Characteristic quantities, such as force-displacement or stress-strain curves, are extracted from the resulting structural responses. The generated data are then preprocessed, normalized, and divided into training, validation, and test datasets. Subsequently, different neural network architectures, including Feedforward Neural Networks, Convolutional Neural Networks, and Recurrent Neural Networks, are systematically trained, validated, and compared with respect to their prediction quality. The aim of this comparison is to determine the most suitable model architecture for inverse parameter identification and to evaluate the influence of the network structure on accuracy, robustness, and generalization capability.
The neural networks are trained to directly predict suitable parameter sets from simulated material or structural responses. Recent studies show that such direct inverse machine-learning approaches are increasingly being established as a promising alternative or complement to classical optimization methods, since they enable rapid reuse of the learned relationship between structural response and material model parameters after the initial training phase. The quality of the predicted parameters is verified through reverse simulations, in which the parameter sets determined by the neural network are used again in LS-DYNA and the resulting curves are compared with the target curves. In addition, a comparison with classical calibration methods, such as LS-OPT, is performed to evaluate the accuracy, robustness, and computational effort of the machine-learning-based method. The overall approach is shown in Figure 1 and includes parameter variation, virtual tests, data preprocessing, network training, inverse parameter prediction, reverse simulation, validation, and comparison with classical optimization methods.

3. Results / Conclusions

The expected results are intended to show to what extent machine-learning methods can provide an efficient alternative to the classical calibration of complex composite material models. The focus is on the achievable prediction accuracy, the generalization capability of the trained network architectures, and the quality of the reverse-simulated material responses. The comparison with established optimization methods enables an assessment of the methodological benefit in terms of computational effort, robustness, and practical applicability. Overall, the approach is intended to contribute to the faster provision of material cards, the acceleration of virtual design processes, and the long-term support of simulation-based verification and certification processes in aerospace engineering.

Influence of 3D-Printed Mesh Energy Directors on Heat Generation in Ultrasonic Welding of Carbon Fiber-Reinforced LMPAEK Laminates

Marta Juanatey Muradas, Mohsen Bahrami, Massimiliano Russenllo
AIMEN Technology Centre, Spain

1. Introduction

Ultrasonic welding of fiber-reinforced thermoplastic composites (FRTP) is a promising technology for aerospace applications, offering reduced weight, manufacturing cost, and assembly time compared with conventional joining methods. A key factor governing weld quality is the design of the energy director (ED), which concentrates ultrasonic energy at the

interface. However, the influence of 3D-printed mesh-type ED architectures on heat generation during sequential welding of carbon fiber-reinforced LMPAEK laminates is not yet fully understood. This work addresses this gap by investigating the effect of ED thickness, infill density, material grade, and weld position on delivered power and interface temperature using an ultrasonic welding system with real-time monitoring. The objective is to identify design guidelines for optimizing ED geometry to improve thermal control and joint quality in aerospace-relevant thermoplastic structures.

2. Methodology

This study employed an experimental campaign on carbon fiber–reinforced LMPAEK laminates joined via ultrasonic welding using a welding station equipped with real-time power and temperature monitoring. Mesh-type energy directors were fabricated using 3D printing to enable controlled variation of geometric and material parameters. Three main factors were investigated: energy director thickness (0.3 mm and 0.6 mm), infill density defined by line spacing (1.75 mm and 3.5 mm), and polymer grade (PEKK-A and PEKK-C) resulting in the configurations shown in Figure 1. In addition, the effect of weld position in sequential welding operations was assessed to capture cumulative thermal effects during multi-weld sequences.



Figure 1. *Evaluated mesh-type energy ED configurations.*

Welding trials were performed under consistent process parameters while electrical power input and surface/interface temperature were recorded throughout each weld cycle. The setup ensured repeatability of force application and ultrasonic energy delivery. Sequential welding configurations were used to evaluate heat accumulation effects in adjacent welds. Data analysis focused on comparing average and peak power delivery and maximum measured temperatures across parameter combinations. Statistical evaluation was performed to identify significant differences between factors and to determine dominant influences on thermal response. Particular attention was given to the interaction between ED geometry and material properties, including loss modulus and thermal conductivity, which influence energy dissipation and heat distribution during welding. The results were used to derive design guidelines for optimizing energy director architecture for improved thermal efficiency and weld quality in aerospace thermoplastic composite assemblies.

3. Results and Conclusions

This study demonstrates that energy director (ED) thickness is the dominant factor governing ultrasonic welding performance in 3D-printed mesh architectures for LMPAEK laminates. As illustrated in the main effects analysis in Figure 2, thinner EDs (0.3 mm) yield higher delivered power area and increased interface temperatures due to superior viscoelastic energy concentration. Material selection also plays a significant role; amorphous-stable PEKK-A demands higher power input than PEKK-C due to its distinct loss modulus and crystallization behavior under processing conditions . Conversely, infill density changes within the evaluated window show no statistically significant impact on the thermal or power response. Additionally, weld position significantly influences cumulative heat buildup during sequential multi-spot welding operations, highlighting the critical need for localized thermal management in manufacturing.

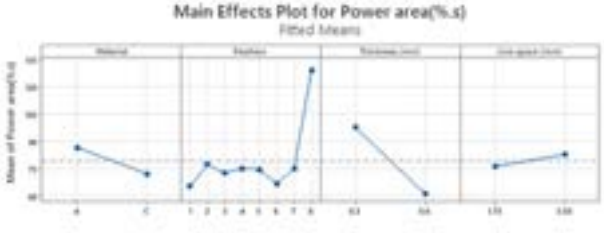


Figure 1. *Main effects plot for weld power area analysis.*

Toward the industrialization of sequential ultrasonic welding for aerospace sector

Mohsen Bahrami, Massimiliano Russello, Marta Juanatey Muradas, Enrico Chemello, Elena Senin Rodriguez

Aimen Technology Center, Spain

1. Introduction

Current industrial trends in aeronautical composite manufacturing, driven by initiatives such as Clean Aviation, focus on advancing the TRL of assembly processes. Sequential ultrasonic welding (USW) has emerged as a highly attractive joining method for thermoplastic composites due to its speed, repeatability, and compatibility with automation−key enablers for future sustainable and high-rate aircraft production.

2. Methodology

This research explores in-situ monitoring and correlation with weld quality in industrial scenarios. Robust processing needs monitoring and control of both process inputs and outputs. In this framework, welding parameters (amplitude, time, and pressure) are categorized as primary inputs. On the other hand, process power serves as a critical output, directly affecting process robustness, weld area, microstructure, and joint strength. While parameter optimization is fundamental, correlating inputs and real-time outcomes, such as power profiles and thermal evolution, is vital for industrial scaling.

This work presents an experimental campaign conducted on thick (4mm) thermoplastic composite laminates (PEEK/CF), representative of aeronautical components like stringers and clips. The study systematically evaluates the effect of welding parameter variations on weld quality, reflected through power consumption, microstructure, and single lap shear strength.

3. Results

Results confirm that optimized parameters successfully overcome key bottlenecks in composites joining. This reinforces the potential of SUW as a reliable, sustainable, and scalable process for industrial-grade, high-rate aeronautical assembly.
In more detail, the best set of welding parameters resulted in a shear strength of 37.1 MPa with less than 1% overall porosity through the thickness of the welded laminates (Fig.1).
Regarding the correlation between inputs and outputs, findings indicate that power is primarily influenced by amplitude, in contrast to the pressure which does not show a clear effect on power trends (Fig.2).

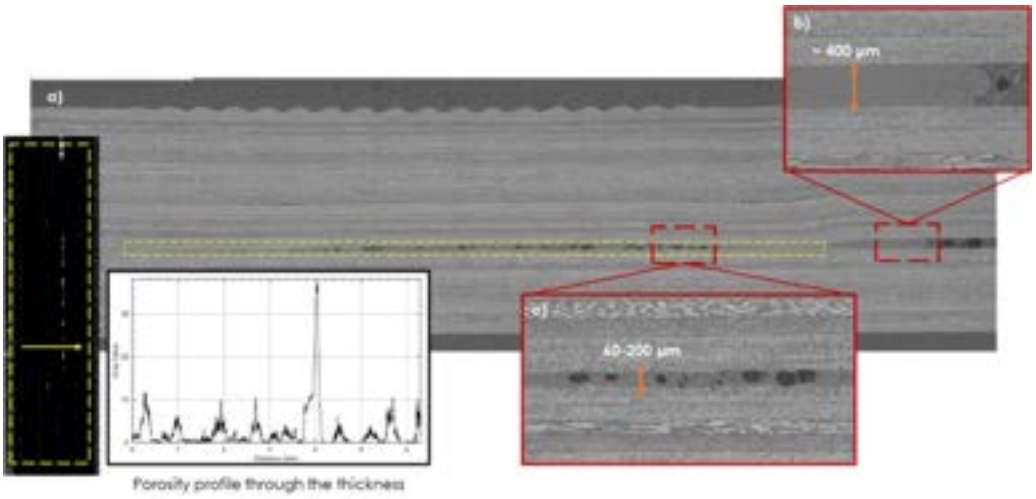


Figure 1. *The cross-sectional micrograph of the welded laminates.*

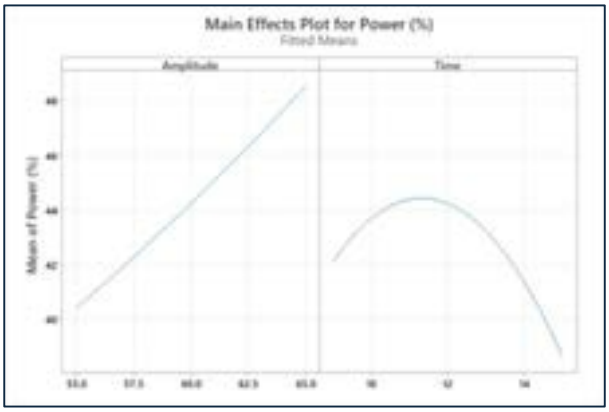


Figure 2. *Correlation of output power with amplitude and welding time.*

A Holistic Sustainability Framework for Early-Stage Aircraft Conceptual Design Using Bayesian Networks

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[2]Cranfield University, UK

1. Introduction / Objectives

Sustainability is a key requirement in contemporary engineering design, yet it remains challenging to quantify due to its inherently multidimensional nature. In aircraft conceptual design, early design decisions strongly influence life-cycle performance, cost, environmental impact, and long-term circularity potential. However, traditional design approaches often treat these aspects separately, limiting the ability to capture complex interdependencies and evaluate true trade-offs within a unified framework. This work addresses this gap by applying a holistic sustainability framework for early-stage aircraft conceptual design , integrating performance, environmental impact, economic cost, circularity, and social dimensions (Figure 1) into a single multi-objective trade-off problem. Particular emphasis is placed on the use of Bayesian Networks as a probabilistic decision-support tool capable of modeling causal relationships and dependencies between design variables, operational parameters, and sustainability indicators . Unlike deterministic approaches, Bayesian Networks enable reasoning under uncertainty, allowing incomplete or uncertain information to be incorporated directly into the design process. The proposed approach supports both predictive and inferential analysis, enabling designers to evaluate how changes in design parameters influence sustainability outcomes, identify key drivers of system behavior, and assess trade-offs between competing objectives during the conceptual design phase.



Figure 1. *The five pillars of the holistic sustainability framework*

2. Methodology

The proposed framework formulates sustainability as a multi-dimensional evaluation problem across five pillars: performance, environmental impact, economic cost, circularity, and social impact. Performance is assessed using early-stage aircraft metrics such as structural mass and related operational indicators. Environmental impact is quantified through life-cycle CO_2 emissions, covering material production, manufacturing, operational use, and end-of-life stages. Economic cost is similarly evaluated using life-cycle cost (LCC), incorporating raw material extraction, manufacturing, operation, and recycling processes. Both environmental and cost assessments are derived from material- and process-dependent factors, linked to component mass breakdowns obtained at each design iteration. These values are implemented using ANSYS Granta datasets. Circularity is represented through material recyclability and end-of-life recovery potential, reflecting the degree to which materials and components can be reused or recovered. Social impact is modeled through supply-chain risk indicators associated with raw material sourcing and manufacturing locations, following UNEP/SETAC guidelines and relevant ISO standards for social life cycle assessment. To capture uncertainty and causal relationships between variables, a Bayesian Network model is introduced. This probabilistic framework learns dependencies between design inputs and sustainability outputs from simulation data,

3. Results / Conclusions

Preliminary results demonstrate that the proposed framework can successfully capture multi-dimensional trade-offs in early aircraft conceptual design (Figure 2). In particular, strong overlap regions are observed in the design space where performance and sustainability objectives conflict, highlighting the need for integrated decision-making tools rather than single-objective optimization. The Bayesian Network approach enables structured interpretation of these trade-offs by revealing probabilistic relationships between design variables and sustainability outcomes. This provides a more transparent and robust understanding of how design choices influence environmental, economic, and performance metrics.

Ongoing work will extend the framework to a fully holistic life-cycle assessment, including expanded operational and end-of-life modeling. Circularity and social impact dimensions will be fully integrated, alongside additional variables such as manufacturing geography, production routes, and alternative energy carriers. This will enable a more complete representation of sustainability trade-offs in aircraft conceptual design.

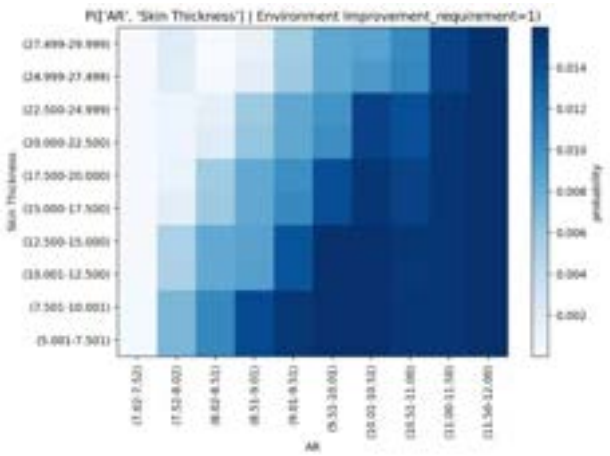


Figure 2. *Bayesian Network conditional probability heatmap showing the relationship between aspect ratio (AR) and skin thickness for improved environmental performance*

Adaptive Test Prioritization for Drone Communication Software: A Constrained Bayesian Contextual Bandit Approach

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AnyWi Technologies, Research & Development

1. Introduction / Objectives

Safety-critical Unmanned Aerial Systems (UAS) require thorough and efficient validation of communication software, particularly for systems intended for operation under stringent certification and safety constraints. As UAS increasingly operate in Beyond Visual Line of Sight (BVLOS) environments, communication subsystems must be verified after software updates to ensure reliable link management, redundancy handling, and regulatory compliance . Existing test prioritisation techniques, however, are often non-adaptive, lack uncertainty modelling for failure probability estimation and provide limited support for strict resource constraints or certification-oriented evidence generation . We present a Constrained Bayesian Contextual Bandit Reinforcement Learning (BCB-RL) framework as a data-driven engineering tool for systematic validation of safety-critical multilink communication subsystems in BVLOS UAS operations. The framework integrates probabilistic failure modelling, risk-aware decision-making, and time-budget-conscious test selection to optimise fault detection, while maintaining requirement traceability and certification alignment. Indeed, the approach reflects EU BVLOS requirements, where operators must demonstrate robustness and continuity of multilink communication under applicable (EU) regulations and the recognised standards, embedding these expectations into test selection to reinforce the safety.

2. Methodology

The proposed initial framework is composed of an adaptive validation environment including a virtualized network emulation environment, a Multilink UAS communication subsystem, and

an orchestration layer responsible for test execution and test outcome collection. The emulator reproduces communication conditions relevant to BVLOS operations, including varying latency and link degradation, which enables controlled evaluation of the multilink communication resilience and redundancy management. On top of this infrastructure, a Constrained Bayesian Contextual Bandit Reinforcement Learning (BCB-RL) agent dynamically prioritises regression tests under strict execution-time constraints.
At each decision step, the BCB-RL agent observes a context vector capturing code change magnitude, historical failure behaviour from a cross-session persistent posterior, regulatory requirement coverage state, and remaining budget. Every test case is linked with a Bayesian logistic regression model estimating context-specific failure probability, with a Gaussian posterior updated via Laplace approximation after each observed result. Persisting this posterior across sessions enables continuous learning without retraining. Test selection is driven by a risk-aware Upper Confidence Bound (UCB) strategy, where risk combines estimated fault impact, requirement criticality, recent code changes, and posterior uncertainty. The use of UCB allows us to balance the exploitation of high-risk tests with the exploration of under-evaluated ones. Severity is computed from static requirement criticality and dynamic code change magnitude, prioritising recently modified safety-critical code. Strict budget constraints are enforced via a feasibility filter, while safety-critical requirements form a mandatory regulatory coverage subset prioritised ahead of UCB scoring to maintain certification compliance. Following execution, outcomes update both posterior estimates and reward signals, which balance severity-weighted fault detection, coverage improvement, and execution cost minimisation. In addition, an evidence layer records requirement-to-test associations, coverage progress, and decision traces as structured auditable artefacts supporting formal safety case development. The framework is evaluated on a Multilink communication test suite derived from regulation-aligned UAS communication requirements, with tests varying in execution cost, requirement coverage, and safety criticality. Performance is assessed against random, greedy severity-based, and standard contextual bandit baselines using APFD, time-to-first-failure, cost efficiency, requirement coverage, and posterior uncertainty reduction across sessions.

3. Results / Conclusions

The proposed BCB-RL framework introduces a structured, data-driven approach to adaptive test prioritisation for safety-critical UAS communication software. Uncertainty-aware UCB selection, together with a cross-session persistent posterior, is designed to shorten time-to-first-failure and enhance Average Percentage of Faults Detected (APFD) compared to static and non-Bayesian benchmarks, especially in sparse failure scenarios where conventional methods lose discrimination. Hard budget enforcement and mandatory safety-requirement coverage are designed to improve certification-oriented validation compared to conventional testing approaches. Beyond performance, the framework's organized evidence production facilitates traceable and auditable validation processes that support applicable (EU) regulations and recognised standards for BVLOS UAV communication systems , supporting the development of certifiable adaptive testing workflows throughout the development lifecycle.

Evaluation of Data Driven Architectures for Virtual Thermal Sensing in Brushless Motors Using Fiber Bragg Grating Sensors

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1. Introduction

The integration of complex mechatronic systems in aerospace and industrial frameworks—such as UAVs, planetary rovers, and robotic manipulators—has elevated the significance of effective thermal management . In compact, low-mass brushless electric motors, excessive temperature rise strictly compromise operational lifespan and system safety . However, conventional internal thermal monitoring is frequently omitted due to stringent cost, size, and weight constraints, forcing motors to operate beneath their true performance potential . To overcome these limitations, this paper validates an innovative virtual sensing methodology. By embedding a Fiber Bragg Grating (FBG) optical sensor into a motor , accurate and electromagnetically immune real-time data is captured. Then, data driven methodologies are used to replicate FBGs behavior to assess the possibility to use them for virtual sensing.

2. Methodology

The experimental architecture is designed to validate the virtual sensing models under realistic operating conditions through three integrated segments: an electrical control system, an optical monitoring setup, and a variable mechanical load mechanism. Actuation and control are managed via a microcontroller that converts speed commands into control signals for an Electronic Speed Controller (ESC) while simultaneously acquiring supply current data. The ESC handles the 12V DC power commutation to generate the rotating magnetic field across the motor phases. To simulate dynamic operating conditions, a variable resistive torque is applied using a dynamo directly coupled to the brushless motor, regulated continuously via a dedicated resistive load circuit. The high-accuracy sensing layer isolates key physical parameters using FBG technology managed by an optical interrogator. Internal stator temperature is measured by an FBG probe carefully positioned within the air gap between adjacent slots to minimize localized mechanical noise from the windings. Simultaneously, motor output torque is evaluated indirectly by measuring structural deformation with an FBG bonded directly to the support arms. Comprehensive data streams from both the FBG interrogator and an Arduino Due microcontroller are synchronized and captured using a custom Python script.

For the virtual thermal sensing task, multiple Machine Learning (ML) and Deep Learning (DL) architectures were rigorously trained and evaluated to balance training overhead, inference speed, and predictive performance. The benchmarked models include Decision Trees, Random Forests, Linear and Nonlinear Support Vector Regression (SVR), Feedforward Neural Networks (FNN) with 1 to 3 fully connected layers, and Convolutional Neural Networks (CNN) with 1 to 3 convolutional layers. Neural network configurations were optimized across broad hyperparameter ranges, including learning rates (10^{-1} to 10^{-7}), batch sizes (2^4 to 2^{10}), and hidden layer dimensions (2^4 to 2^{10}). Model accuracy was cross-examined using three complementary statistical evaluation metrics: Root Mean Squared Error (RMSE) to penalize significant outliers, Mean Absolute Percentage Error (MAPE) for normalized comparative

visibility, and Mean Bias Error (MBE) to identify systematic overestimation or underestimation tendencies.

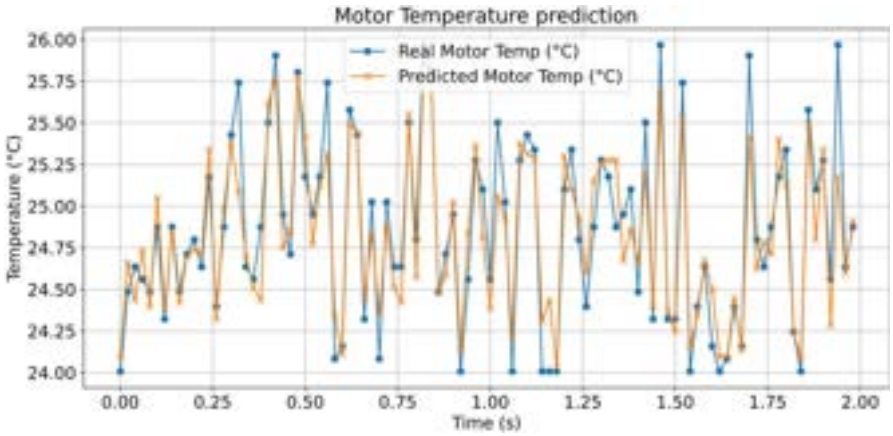


Figure 1. *An example of prediction results from the CNN with three convolutional layers.*

3. Results and Conclusions

The comparative analysis highlights a distinct performance gap between linear and non-linear models, confirming the highly non-linear nature of internal motor thermal dynamics. Linear SVR exhibited the lowest accuracy, whereas neural network topologies consistently outperformed traditional statistical techniques. Specifically, the CNN with three convolutional layers delivered exceptional predictive precision, yielding the lowest global error rates (RMSE of 0.019, MAPE of 0.000152%) and an almost negligible underestimation bias.

This study demonstrates the efficacy of using machine learning architectures coupled with optical FBG sensors for virtual thermal sensing in brushless motors. Future work will expand upon these findings by analyzing the intrinsic computational complexity and exact inference times of these architectures. This will involve deploying the optimized models onto low-power hardware boards to evaluate their practical cost-to-benefit ratio and real-time viability in edge computing aerospace applications.

Dynamic Modulation Switching and Real-Time Kalman Filtering for Airborne RSSI-Based Localization in High-Power Rocketry Missions

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1.Introduction / Objectives

This paper presents the design, simulation, and hardware implementation of an autonomous Search and Rescue (SAR) payload embedded within a 2U CubeSat configuration for the European Rocketry Challenge (EuRoC). The mission focuses on the real-time localization of lost mountaineers or hikers emitting distress signals in remote, mountainous terrains during a rocket's parachute descent phase from an apogee of 3000 meters. Overcoming the inherent

limitations of standard Received Signal Strength Indication (RSSI) localization—namely log-distance flattening and multipath fading caused by pendulum oscillations—is critical. To address this, we introduce a novel Dynamic Modulation Switching (DMS) subsystem integrated with an Extended Kalman Filter (EKF). The main objective is to demonstrate that an adaptive, software-driven RF infrastructure can complete rapid localization convergence under highly dynamic flight profiles while strictly complying with international spectrum regulations. This approach replaces heavy tracker systems with optimized, lightweight commercial off-the-shelf components.

2. Methodology

The payload architecture utilizes an array of four directional 869.5 MHz transceivers isolated by a cross-shaped electromagnetic RF baffle, providing a directional antenna gain of Delta G = 15 dBi. The core innovation lies in altitude-dependent telemetry adaptive routing. At high altitudes (3000m down to 1200m), the system operates in LoRa (SF7 / 250kHz) mode at a low update rate (~3.85 Hz), leveraging a -119 dBm receiver sensitivity to secure the radio link margin over long distances.

Upon breaching a 1200m threshold, monitored by an onboard barometric sensor, the flight computer dynamically reconfigures the RF front-end via SPI to GFSK modulation (100 kbps) operating at 25 Hz. This shift provides an influx of over 6000 telemetry points at lower altitudes where the geometric dilution of precision is minimized, enabling the EKF to converge rapidly.

The system hardware is managed by a Raspberry Pi Zero 2W running a custom-compiled RT-PREEMPT Real-Time Linux Kernel. This setup utilizes Direct Memory Access (DMA) to handle the deterministic scheduling of 9 SPI peripherals on a shared bus without scheduler jitter. To mitigate mechanical stress during launch and parachute deployment shock, a high-G industrial IMU (Bosch BMI088, +/-24g) is paired with a military-grade magneto-inductive sensor (PNI RM3100) [8]. The raw inertial data feed a localized Madgwick orientation filter to continuously update the payload's yaw, roll, and pitch. This allows the ground-station EKF to compensate for pendulum attitude alterations in real time. Frequency isolation and prevention of self-jamming on the primary 869.5 MHz SAR receivers are achieved by utilizing a dedicated, independent 5th LoRa downlink operating at 433 MHz.

Finally, to comply with the 10% duty cycle regulations mandated by ETSI EN 300 220-1 and the Portuguese ANACOM authority, software-level rate limiters restrict the LoRa phase to 9.6% and the GFSK phase to 8.0% duty cycle.

3. Results / Conclusions

The proposed architecture was validated using comprehensive Software-in-the-Loop (SIL) trajectory simulations that incorporated damped harmonic pendulum oscillations. The simulation results verified the mathematical stability, real-time determinism, and rapid convergence of the adaptive filtering scheme under realistic flight conditions. The Extended Kalman Filter successfully processed the high-rate GFSK RSSI data below 1200m, allowing the system to achieve a Circular Error Probable (CEP) of less than 40 meters upon landing. Furthermore, the hardcoded software rate limiters successfully maintained spectrum compliance throughout both flight phases. In conclusion, this research demonstrates that combining dynamic modulation switching with real-time state estimation provides a highly reliable, low-cost, and spectrum-compliant solution for airborne tracking. The architecture sets a scalable standard for future CubeSat-based search and rescue deployment and autonomous aerospace recovery missions.

Review of Data-Driven Surrogate Models for Structural Analysis of Mounting Systems for Electrified Aero Engines

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German Aerospace Center (DLR), Germany

1. Introduction / Objectives

The integration of components and subsystems in electrified aero engines requires knowledge in and communication between different fields of engineering. The set-up of various integration architectures, the selection of the most fitting concept, the design of engine components and their subsequent topology optimizations requires a quick and adaptive system design approach. Considering integration and safety aspects in the preliminary design phase helps narrowing down the multitude of different integration concepts, provides constraints for engine component designs and accelerates the development process. One aspect to consider for integration is the structural analysis of an engine mounting system. The engine mounting structure is a critical system, which has to ensure structural integrity given aviation specific boundary conditions such as, for instance, heavy landing, bird strike or propeller-induced vibrations.

2. Methology

This paper aims to investigate different types of data-driven surrogate models, which could be applied for the structural analysis of engine mounting systems. A literature review on physics-informed neural networks, k-nearest neighbor regression and Gaussian process regression was carried out. The applicability of models is graded by direct comparison based on the most relevant evaluation criteria for component integration given the specific requirements derived for the use case.

3. Results

The application of data-driven surrogate models yields fast results and is therefore being evaluated for the application to the use case of a beam and truss assembly to mount a turboprop engine. As a reference an FEM-based analysis of the use case is carried out and presented in this paper. The highest graded surrogate model is the most fitting for an adaptive and fast approach in mounting structure design for the development of electrified aero engines.

Data-Driven Calibration of GEKO Turbulence Model Coefficients for Transonic Aerodynamic Flows

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Accurate prediction of transonic flows remains one of the most demanding problems in computational fluid dynamics. The simultaneous presence of subsonic and supersonic regions, the formation of shock waves, and their interaction with the boundary layer give rise

to flow features whose prediction is strongly sensitive to the turbulence closure adopted. Reynolds-Averaged Navier–Stokes (RANS) simulations remain the standard tool of industrial aerodynamic design, owing to their favourable trade-off between accuracy and computational cost; their predictive fidelity, however, depends not only on the turbulence model itself but, more subtly, on the empirical closure coefficients that the model embeds. These coefficients are typically calibrated on canonical equilibrium flows and, when transferred to transonic regimes, frequently lead to a systematic misprediction of the shock location and to a distortion of the downstream pressure recovery. In current practice, mitigating these deficiencies relies on case-by-case recalibration carried out manually by experienced analysts, an approach that is labour-intensive, poorly reproducible, and difficult to generalise across configurations. The present study addresses this limitation by replacing expert-driven tuning with, first, an automated and data-driven calibration of the turbulence closure and, ultimately, a predictive framework capable of supplying optimal coefficients for previously unseen geometries without recourse to additional CFD simulations .

The study adopts the Generalized k-ω (GEKO) turbulence model, whose free coefficients (C_{sep}, C_{nw}, C_{mix}) can be tuned without modifying the underlying transport equations, which makes it well suited to targeted recalibration across flow regimes and geometries . A two-phase surrogate-based optimization pipeline is developed. An initial Design of Experiments based on Latin Hypercube Sampling explores the coefficient space; an adaptive infill strategy then refines the surrogate, coupling Radial Basis Function (RBF) interpolation with a Jones-type acquisition criterion to drive the search toward the optimum . For each of five benchmarks: the RAE2822 airfoil, the ONERA OAT15A supercritical profile, the NASA wall-mounted hump, the curved backward-facing step (CBFS), and the axisymmetric transonic bump the optimal coefficients are obtained by minimizing the RMSE between computed and experimental pressure-coefficient distributions. The recalibration markedly improves shock capturing and pressure recovery relative to the default closure: on the axisymmetric transonic bump the C_p RMSE decreases from 0.0338 to 0.0165 (Figure. 1), while on the NASA hump the optimized coefficients recover both the experimental shock position and the post-shock pressure plateau that the baseline GEKO model fails to capture (Figure. 1).

The principal contribution of this work is a geometry-aware meta-surrogate that turns these case-specific optima into a predictive model. Each configuration is described by two sets of inputs: a compact set of Class Shape Transformation (CST) coefficients that encode its airfoil section, and the governing flow parameters (Mach number, Reynolds number, and angle of attack). Together these form the input feature vector of a Gaussian Process Regression (GPR) model. The GPR is trained on the optimized-coefficient database produced by the benchmark campaign, and it learns how geometry and flow conditions map to the optimal GEKO coefficients. Once trained, the model assigns a calibrated closure to a new configuration directly from its shape, without running a new optimization

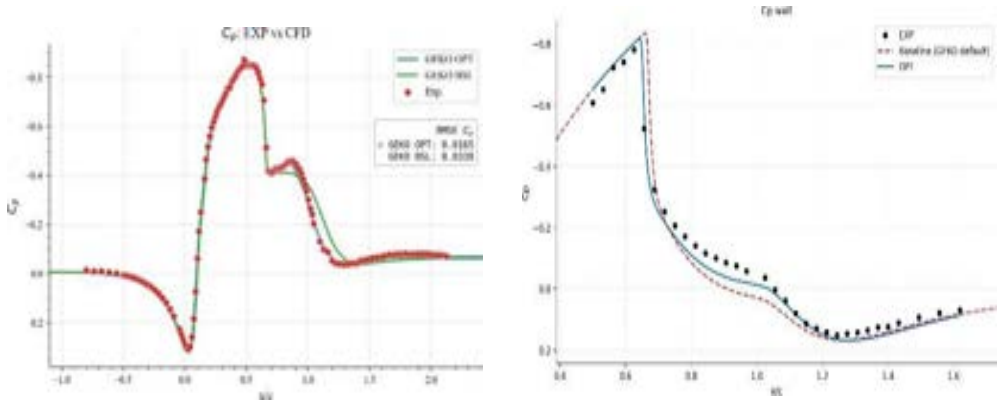


***Figure 1**: On the left: Axisymmetric transonic bump: optimized vs. default GEKO closure. On the right: NASA wall-mounted hump: optimized vs. default GEKO closure.*

campaign or the CFD evaluations it requires. The framework is assessed on the Benchmark Supercritical Wing (BSCW), a three-dimensional test case excluded from the training set. Relative to the default GEKO closure, the GPR-predicted coefficients reduce the overall C_p RMSE from 6.1% to 5.0%, and the upper-surface (shock-side) error from 8.0% to 4.7% (Figure. 2). The model therefore extrapolates beyond its calibration database, even to a higher-dimensional flow. By combining surrogate-based optimization with geometry-aware machine learning, the proposed methodology provides a systematic and automated route to turbulence-model calibration, removing the reliance on manual tuning and expert judgement. It is a concrete step toward predictive RANS simulation for transonic aerodynamic design.

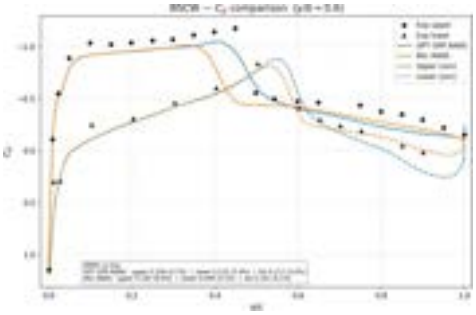


Figure 2: Pressure coefficient distribution on the BSCW ($y/b = 0.6$): default GEKO closure vs. GPR-predicted optimal coefficients. The predicted coefficients lower the total C_p RMSE from 6.1% to 5.0% and the upper-surface error from 8.0% to 4.7%.

Certification & Regulatory Frameworks in Aviation

Chaired by:
Prof. Joël Jézégou (ISAE-SUPAERO, France)

Simulation-Based Framework for UAS Operational Risk Assessment and Compliance with EASA and Transport Canada SORA-Based Regulatory Approaches

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[2]University of Victoria Centre for Aerospace Research, Canada

1. Introduction / Objectives

The growing need for the risk assessment of Unmanned Aerial Systems (UAS) operations requires robust and repeatable methods to demonstrate compliance with risk-based

regulatory frameworks such as the Specific Operations Risk Assessment (SORA). However, the verification of operational scenarios addressing regulatory safety objectives remains challenging due to limited coverage of flight tests, high costs, and safety constraints. The SORA methodology, based on the requirements of JARUS and adopted by EASA and Transport Canada, requires the use of risk mitigation measures and the presentation of reliable evidence of their effectiveness. One of the accepted pieces of evidence is the results of simulations, which justified the development of the ESIM-SORA simulation environment.

2. Methodology

This study presented the ESIM-SORA simulation environment, developed to support the verification and demonstration of operational risk evaluation and risk-mitigation strategies under the increasing complexity of UAS operations. The simulation framework integrates nonlinear multirotor UAV flight dynamics, environmental conditions, and configurable operational constraints. It allows for the definition and execution of organised scenarios, including propulsion failure, navigation failure, command and control loss, return-to-home, and emergency landing procedures.
In addition, ESIM-SORA incorporates crash fragmentation area modelling, kinetic energy estimation upon impact, and computation of contingency volume and ground risk buffer with wind adaptation and vehicle-specific parameters. The framework supports multiple UAV platforms and configurations, with the ability to incorporate additional vehicle models, enabling comparative analysis and mission-level selection of the most suitable platform.
As a result, ESIM-SORA allows key scenarios to be tested virtually, leading to cost reduction of real testing Furthermore, the environment supports training activities by allowing student pilots and developing UAS operators to explore realistic operational scenarios within a repeatable and controlled simulation framework.

3. Results / Conclusions

A scenario-based analysis was performed to evaluate the extent to which the developed simulation environment may be used to support compliance with European and Canadian regulatory approaches. ESIM-SORA was applied to a representative BVLOS scenario derived from a planned flight campaign in Canada and Poland, currently used to support its planning. The results demonstrate the potential of the framework as a tool for digital validation, contributing to the development of safety cases and future UAS certification processes.

Improving Efficiency and Modularity for the Certification of New Airborne Hardware

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1. Introduction / Objectives

Certification for avionics components is often a time-consuming task, especially when introducing a new technology or system to an aircraft. Combine this with the necessary changes to processes and methodologies as mandated by DO-254, and the initial entry hurdle presents a challenge for anyone trying to obtain certification when they cannot rely

on established methods. Therefore, most commonly found avionics providers and developers are established companies or individuals that boast significant experience. This research aims at providing methods that can accelerate the certification process for new technologies by analyzing the common pitfalls of certification and proposing structures that can help in development. Furthermore, a new approach to developing systems that allows for quicker application to new use cases will be explored.

2. Methodology

The approach starts with an analysis of the certification approach as specified in DO-254, and a representative mock certification process using an airborne smart camera. The camera is chosen for its variety in possible use cases and its relevancy to modern aviation endeavors. This camera is used as a reference avionic component for the research, and the camera is conceptualized for compliance with DO-254. With a compliant avionic component, the processes and methods for certification can be explained clearly. Using the defined use case as a basis, the difficulties faced when trying to obtain certification are highlighted and solutions for easier processes are proposed.

Due to the nature of DO-254 and certification, any significant change to the component leads to the invalidation of the certification. Therefore, trying to reuse a hardware component for a different use case is often infeasible, especially when these use cases result in differing criticalities or requirements. In such a case, even though the component itself has already been certified for a different use case once, the certification process needs to be redone. Especially the chosen smart camera use case is affected by this, because modern aviation and Unmanned Aerial Vehicles (UAV) have a plethora of different use cases and requirements for cameras, meaning each new system would have to be certified individually. To mitigate the time and resource drain this causes, the study also explores the use of different modular architectures and design approaches to allow for different use cases without the need for a complete recertification.

Both aspects of this study combine to form a concise overview of certification and provide some examples for how a certification process can be completed quicker and with more flexibility.

3. Results / Conclusions

Research is still ongoing; the results of the study will be a comprehensive overview of the certification process and explanations of efficient certification approaches using the previously mentioned camera. Most studies or articles found in regard to certification are vague and lack proper detail, and this study focuses on giving an overview and subsequently providing impulses for a quicker certification and more modular end component. Using this approach will ultimately result in an easier certification process and more flexibility with the use of the component. The study results in a methodology for certification that acts as a supporting tool alongside the official documentation. Furthermore, it will help provide a better understanding of certification and use concrete examples to present a new way of developing for certification, which will help make certification for new technologies or new companies in the field easier.

Forecasting the Socioeconomic Impacts of Innovative Air Mobility: A Welfare Assessment Framework

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Future Needs Management Consulting Ltd

1. Introduction

Innovative Air Mobility (IAM) is emerging as yet another addition to the cities' landscape that will permanently influence urban transportation systems. As the European Union develops its Sustainable and Smart Mobility Strategy and Green Deal, the integration of new aviation technologies into the European economy requires significant consideration of social cohesion, equity, and resilience. Current IAM setups are concerned predominantly with technical and operational feasibility, creating a need for policy ready, accessible models of the socioeconomic impacts of IAM. Recent reviews confirm that socio economic impact assessment remains fragmented, often relying on insufficient and scattered indicators. This paper addresses this gap by introducing a theoretical framework, developed within the EU funded ImAFUSA project to link IAM deployment scenarios to real estate costs and GDP per capita, aiding policymakers in anticipating welfare trade-offs to support inclusive urban aviation strategies aligned with European policies.

2. Methodology

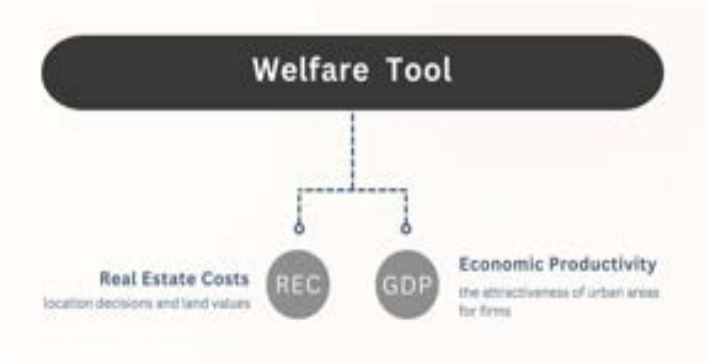


Figure 1. *Visual representation of the welfare tool*

To develop and validate this research, a literature review was first conducted to identify the foundational parameters that drive socioeconomic impacts in urban environments. Our framework integrates urban spatial equilibrium theory, as formalized by Straubinger et al., with accessibility driven decision making. The core premise is that IAM's primary effect is the alteration of urban spatial accessibility, which directly influences two welfare critical outcomes: (i) location decisions and land values (proxied by real estate costs) and (ii) the attractiveness of urban areas for firms (proxied by economic productivity – GDP per capita). Rather than relying on unavailable historical IAM data, we model these outcomes as functions of key urban variables that can be varied in scenario simulations. Specifically, real estate costs are influenced by IAM availability, wages, and population density, while economic productivity is driven by IAM availability, employment density, and human capital. This method simulates city specific scenarios for IAM deployment effects on real estate costs and GDP per capita, providing insights into trends rather than precise estimates. The tool

allows users to input city specific data (e.g., population density, wage levels, job density, education rates, and assumed IAM availability) and explore expected changes under different IAM deployment scenarios. This approach responds directly to the need for comprehensive socio-economic indicator frameworks in IAM assessment.

3. Conclusion

The theoretical framework reveals that IAM's welfare impacts are context dependent and unevenly distributed. These impacts will be affected by the location of vertiports or vertipads. In cities with high education levels and job clustering, IAM may generate significant GDP gains by enhancing labor market efficiency and fostering agglomeration. Conversely, in high density areas, improved accessibility could drive sharp increases in housing costs, raising equity concerns. Empirical studies show that deploying IAM on a medium scale enhances regional resilience; however, large scale deployment can bring spatial inequality unless implementation is carefully controlled. The insights above show that IAM can boost economic activity and urban resilience by offering mobility alternatives that prevent shock spillovers to existing networks, but it can also increase inequality rather than reduce it. This framework provides a platform for policy actions that maximize welfare gains from IAM while minimizing possible negative distributional impacts.

Certification of Hydrogen-Powered Aircraft: A Three-Layer Mapping Approach to Address Regulatory Readiness, Knowledge Gaps, and Safety Risks

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1. Introduction / Objectives

In the pursuit of decarbonisation, the aviation industry is exploring liquid hydrogen as a potential pathway towards realising carbon neutrality by 2050. Conventional kerosene combustion turbofan engines benefit from decades of development whereas hydrogen (H2) combustion in aircraft is less well understood. While H2 offers significant environmental benefits, its integration into aircraft and the associated safety and development rigor required of the industry pose serious challenges to the realisation of H2 fuel systems and engines. Presently, current certification bases established by EASA do not account for the use of hydrogen. To facilitate the technology readiness maturation of aerospace hydrogen technologies, the certification readiness level (CRL) must mature in tandem.

This paper casts its effort towards assessing the level of alignment between regulatory insufficiencies, knowledge gaps, and high-risk areas. The objective is to identify and prioritise H2 propulsion systems research areas to define detailed technical requirements necessary for informing the Means of Compliance for hydrogen combustion in a turbofan engine in the context of the CAVENDISH project.

2. Methodology

The applicable Certification Specifications CS-25 and CS-E are reviewed and undergo a

qualitative categorisation-based engineering judgement for their applicability to hydrogen technology. The articles are categorised as either: articles that remain applicable without change; articles that are applicable but require rewording to account for hydrogen specifically; articles where only the safety intent is applicable and require translation into new requirements applicable to hydrogen; and articles that are not applicable.
To ensure that amended certification articles continue to meet the intended safety objectives, the underlying hydrogen knowledge base was assessed revealing gaps in both fundamental understanding of hydrogen-related phenomena and the associated technical knowledge. The missing knowledge topics are further examined through a targeted literature study to evaluate their maturity-level, resulting in a mapping between key hydrogen research topics and the relevant CS articles.
To complement this work, a conceptual safety assessment is performed. Based on a conceptual design, a functional and logical architecture of a hydrogen propulsion system is defined within the context of the CAVENDISH project, establishing the architectural basis for a liquid hydrogen (LH_2) system integrated into a Flight Test Vehicle (FTV). Through a model-based system safety assessment, a failure model of the LH2 fuel system is created to evaluate failure propagation through a cascading failures analysis in combination with intrinsic hazards and particular risks analysis. Following the safety assessment, a safety risk matrix is introduced to prioritise critical areas for development and verification, aligning with the philosophy of EASA's Level of Involvement (LoI) assessment in certification projects. This matrix supports a risk-based approach by focusing on system elements that are key contributors in fault tree analyses, and present a high risk of unidentified non-compliance due to novelty and complexity. In doing so, it highlights components and integrations with the greatest risk for overall aircraft safety.
The final step of the methodology correlates the outcomes of the three preceding analyses: the regulatory gap analysis, the knowledge gap analysis, and the safety risk assessment. The objective is identify critical safety and certification bottlenecks, where limitations in the regulatory framework coincide with incomplete knowledge and elevated safety risks, and highlighting priority areas for further development and certification focus.

3. Results / Conclusions

Certification feasibility is conditional on resolving the alignment between regulatory provisions, knowledge maturity and safety risk. The present work realises a formulation of a three-layer mapping that synthesises the regulatory framework. Layer 1 provides the regulatory gaps/topic pertaining to CS-25 and CS-E, while layer 2 outlines current state of knowledge availability related to each regulatory topic. Finally, layer 3 allocates safety risk to each topic. This framework enables the evaluation of whether current knowledge on aircraft regulations address safety-relevant hydrogen knowledge gaps and highlights the regulatory areas that are linked to high-risk failure conditions. The presented work paves the way for the development of a targeted regulatory roadmap that is conscious of the maturity of hydrogen knowledge and the associated safety risks.

Acknowledgement: The financial support by the European Union through the Clean Aviation project Cavendish is acknowledged. (Consortium for the AdVent of aero-Engine Demonstration and aircraft Integration Strategy with Hydrogen), grant agreement n° 101102000, EU/HORIZON-JUClean-Aviation-2022-0. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Certification of Hydrogen-Powered Aircraft: Lessons Learned and Mitigation Strategies for Risk-Informed Development

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1. Introduction / Objectives

The development of hydrogen-powered aviation systems introduces significant challenges in aligning emerging technologies with existing certification frameworks. While analytical approaches can identify regulatory gaps, knowledge deficiencies, and safety risks , experimental validation is essential to confirm assumptions and demonstrate technological feasibility. Current certification frameworks, such as Certification Specifications CS-25 and CS-E, were not developed with hydrogen systems in mind, requiring adaptation to address novel hazards and system behaviours. Building on a structured prioritization of critical areas, this paper builds on lessons learned from experimental activities within the CAVENDISH project, to derive insights relevant to hydrogen direct combustion in aero-engines. The work aims to support the demonstration of technological and industrial feasibility, bridging the gap between theoretical analysis and real-world implementation.

2. Methodology

The methodology builds upon prioritised high-impact topics identified through a three-layer mapping approach, where regulatory gaps, lack of knowledge maturity, and safety risks converge. These topics provide the basis for a structured, evidence-based analysis of project outcomes, ensuring continuity with prior analytical work and addressing key research questions related to certification adequacy, applicability, and risk mitigation.

Central to the study is the integration of experimental validation activities aimed at demonstrating the maturity and feasibility of hydrogen direct combustion technologies in an aero-engine context. Experimental observations are analysed to assess system behaviour under representative operating conditions and to evaluate the validity of assumptions made in earlier safety and regulatory analyses.

It should be noted that, while the experimental activities are conducted using gaseous hydrogen for practical and testing purposes, the certification perspective and safety considerations are primarily developed with liquid hydrogen system architecture in mind, reflecting the expected implementation in aviation applications.

Lessons learned are systematically extracted through a detailed review of system design iterations, safety assessment updates, and challenges encountered when applying existing certification specifications (CS-25 and CS-E) to hydrogen propulsion systems. This includes identifying where certification provisions prove insufficient, non-applicable, or difficult to interpret in practice, and how knowledge gaps limit the definition of compliant requirements.

For each identified challenge, mitigation strategies are evaluated, including architectural design adaptations, implementation of additional safety barriers, and refinement of requirement interpretations to preserve intended safety objectives. Particular emphasis is placed on assessing the extent to which these mitigation strategies reduce uncertainty and effectively address safety risks identified in prior system safety assessments.

Finally, the findings are synthesised into a structured set of lessons learned, explicitly linked to the high-priority topics identified in the previous analysis, and complemented by reflections on their implications for future hydrogen aviation initiatives.

3. Results / Conclusions

The results demonstrate how experimental validation and project experience provide evidence-based insight into the adequacy and limitations of existing certification frameworks for hydrogen-powered aviation. The lessons learned highlight gaps between regulatory assumptions, knowledge maturity, and observed system behaviour, as well as the practical challenges encountered in achieving compliance to safety objectives.
The study shows that targeted mitigation strategies, supported by experimental validation, can effectively reduce safety risk and refine certification approaches, although residual uncertainties remain in areas with limited knowledge maturity. The integration of experimental evidence with safety and regulatory analyses significantly strengthens risk-informed development and improves alignment between emerging technologies and certification requirements.
Certification feasibility is conditional on resolving the alignment between regulatory provisions, knowledge maturity and safety risk, as demonstrated through the integrated analysis.

Acknowledgement: The financial support by the European Union through the Clean Aviation project Cavendish is acknowledged. (Consortium for the AdVent of aero-Engine Demonstration and aircraft Integration Strategy with Hydrogen), grant agreement n° 101102000, EU/HORIZON-JUClean-Aviation-2022-0.

Scaffolding Regulatory Compliant Data Products for Aerospace Data Ecosystems

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1. Introduction / Objectives

The European ESPR and REACH regulations require aerospace manufacturers to provide structured, machine-readable product and material data across multiple supply-chain tiers. Current practice relies on PDF declarations, supplier portals and manual compliance dossiers, producing redundant effort, incompatible formats and unverified conformity. Data Products such as Digital Product Passports (DPP) and Digital Material Passports (DMP) paired with Data Spaces are gaining traction, though no validated aerospace-specific framework yet combines formal data-product governance for the aerospace supply chain.
This paper presents a data-product lifecycle governance framework, situated within a Data Ecosystem, to ensure regulatory compliance across the aerospace supply chain, including but not limited to ESPR and REACH.
The framework integrates structured governance mechanisms with semantic data modeling to enable traceable, interoperable and reusable data products.

2. Methodology

This study applies the Design Science Research Methodology (DSRM) following Peffers et al. .

The research builds upon a data product modeling process, which defines a four-phase governance workflow with dedicated roles including Domain Experts, Modeling Experts, Use Case Owners, a Modeling Board and a cross-competence Modeling Team (see ***Figure 1.***).
In Phase 1, a dual requirements analysis is conducted. First, regulatory compliance criteria are systematically extracted from applicable regulations and standards (e.g., ESPR, REACH, and certification requirements such as material certificates per EN 10204:2005 and EN 9100 , , ,) focusing on data obligations relevant to aerospace material and product declarations. Second, an established collaborative data product governance process (see ***Figure 1.***) is analyzed to identify structural gaps regarding regulatory traceability, conformity verification and lifecycle state management for data products.
In Phase 2, the governance model is designed to extend the established process with regulatory lifecycle mechanisms. These include compliance-oriented quality gates, lifecycle state definitions aligned with declaration requirements, and role extensions for regulatory verification. The semantic formalization follows principles of ontology engineering methodologies such as LOT and is implemented using semantic web technologies to ensure machine readability and interoperability, particularly, though not exclusively, within Data Space architectures.
In Phase 3, the framework is instantiated through a representative aerospace supply-chain scenario derived from an active aerospace supply chain use case representing 15 participants spanning Tier 5 to OEM, demonstrating how a data product traverses the governed lifecycle from initial use-case need through modeling, compliance verification and provisioning.
In Phase 4, the artefact is evaluated through expert reviews, with industry partners from 30 partners from the European aerospace sector, including OEMs, Tier suppliers, and research organizations. Evaluation criteria include regulatory coverage completeness, practical feasibility within existing workflows, and alignment with Data Space interoperability requirements.

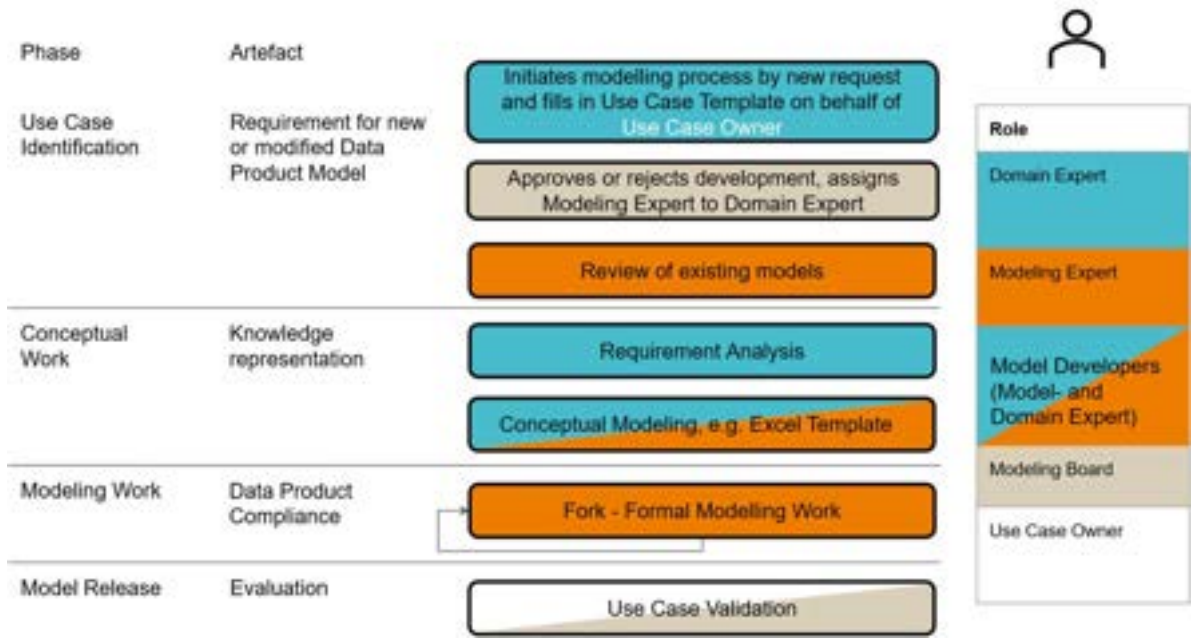


Figure 1. *Collaborative Governance Model for Data Product derivation in Aerospace Ecosystems*

2. *Results / Conclusions*

Expert validation against a real aerospace supply chain confirms regulatory coverage, practical feasibility and interoperability across heterogeneous organizational contexts. The results show that a combination of formal data product governance, input from domain experts and semantic modelling can replace fragmented, document-based compliance practices with a scalable, machine-readable and verifiable approach, thereby eliminating redundant manual effort. The framework delivers a Data Product Store under the control of an independent association, enabling ecosystem participants to retrieve and provision the latest compliant data product models without redundant effort.

However, validation reveals that the predominant barrier to adoption is not technical but organizational: existing procurement structures, qualification processes and contractual frameworks are built around document-based exchange. Transitioning to governed, machine-readable data products requires structural change across established supply-chain relationships. Further research is needed on change management strategies, incentive models and incremental migration paths that enable adoption without disrupting certified processes.

Sustainability and circularity in the design process in aviation

Chaired by:
Prof. Angelos Filippatos (University of Patras, Greece) & Ms. Ligeia Paletti (German Aerospace Center (DLR), Germany)

The impact of circular economy on the future European long-range aircraft

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Circular economy is a pillar of the European Green Deal; a transition to a circular economy is proven to support competitiveness, enhance the resilience of supply chains and reduce material availability risks, next to reducing the environmental impact of human activities on the planet. Those benefits have been demonstrated in several sectors beyond aviation. The application of circular economy principles in the aviation sector is limited to the reduction of resource usage (e.g. additive manufacturing or lightweight design) and to end-of-life strategies (e.g. aircraft recycling). Also, current assessments of circularity do not reflect the character of circular economy, detailed in the ISO 59004:2024, as they are limited to end-of-life LCA or to input/output material flows.
Applying circular economy principles holistically can provide mitigation strategies for the supply chain and material availability challenges caused to the aviation sector by the current geopolitical situation. To monitor progresses, a circularity performance assessment methodology for aviation aligned with the ISO 59004:2024 must be developed and applied as part of the aviation impact assessments.
A comprehensive framework of definitions for translating circular economy concepts into aviation and a circularity performance methodology have been developed in previous work by some of the authors. The former allows aircraft designers to understand what circular economy principles can be applied to the specific aircraft under consideration, while the latter allows to assess the impact of design choices on the circularity performance of the aircraft. In this work, the approach is expanded to incorporate a decision-making methodology based on utility functions. The rationale for including utility functions in the decision-making approach is to ensure that design decisions are contextualized with current and future aviation scenarios and to account for (aviation and non) stakeholders' preferences. The scenarios and the stakeholders are selected based on technological, societal, regulatory and political considerations.
In this work, the above-described approach is applied to the baseline and reference aircraft defined in the EXAELIA project.
First, the circularity performance assessment is carried out for the two aircraft configurations. The methodology determines an overall circularity performance for each configuration, and also performances for each resource management action [1,3]. Those results enable the identification of possible areas of improvements; acting on those can increase the overall circularity of the aircraft, for example by proposing design changes (such as different materials) or by focusing on specific life cycle phases (e.g. end-of-life).
Then, the results of the assessments are re-evaluated in the light of the preferences of the stakeholder(s) and of the defined scenarios. This allows the possible design choices to be prioritized based on criteria decided by the stakeholders or based on the scenario

considered (e.g. the effect of specific regulations being implemented).
The outcomes of the developed approach can increase the resilience and competitiveness of the future long-range aircraft investigated within EXAELIA project, ensuring aviation contributes to the objectives of the European Green Deal and of ACARE's Fly the Green Deal.

From sustainability criteria and LCA data to priorities for aircraft design: an introductory approach

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1. Introduction / Objectives

Development of aircraft systems results in long development cycles and extended operational lifespans . These characteristics make early design decisions disproportionately impactful for sustainability. Therefore, aerospace companies need to integrate a holistic sustainability perspective in requirement setting. Previous research has presented an approach to defining a sustainability design space, with identified strategic long-term socio-ecological criteria and linked tactical design guidelines to be applied prior to requirements setting . Recent studies propose new approaches to integrate sustainability assessments alongside technical and economic requirements. A gap remains in effectively supporting companies as engineers navigate complex trade-offs among economic, environmental, and social impacts during early design stages . This research aims to identify a generic set of prioritized socio-ecological sustainability criteria for the design of aircraft systems and sub-systems through an LCA-data-driven approach, to be used in requirements setting and to guide trade-off management.

2. Methodology

The research methodology was divided into four steps to identify social and environmental criteria applicable to the early-stages of aerospace product development.

1) Criteria identification

A literature search was conducted using Scopus on the 12th March 2026, with the following keywords in the title or abstract: "(social OR ecological OR sustainability OR environmental) AND (criteria OR requirement OR indicator) AND ("Product Development" OR "early design" OR "conceptual design" OR "early stage")". The search was further filtered to only include review papers or articles in English within the subject area of engineering and published between 2020 and 2026, yielding 642 studies. 537 papers were eliminated based on their titles to focus on transport-related industries. The papers were examined for product-related social and environmental criteria. Additional sources on social criteria were added since the Scopus literature review yielded mostly ecological criteria. The resulting initial list of criteria contained many redundancies and was refined through aggregation.

2) Criteria filtering

The criteria list was filtered through a focus group with sustainability experts at two case companies, GKN Aerospace and SAAB. Criteria for exclusion were: (a) redundant, (b) not relevant to the company, (c) not relevant to early-stage product development, and (d) not applicable due to other reasons, which were clarified and documented.

3) Criteria prioritisation

The prioritisation of the sustainability criteria is established through review of several lifecycle assessments and a social lifecycle assessment conducted at GKN Aerospace and SAAB. Additional LCA and S-LCA from the literature are included to ensure better coverage of lifecycle phases and aspects not well covered in the company's LCA and S-LCA results, such as noise and end-of-life approaches. In parallel, 3 sustainability experts, 3 R&D managers and strategists, and 3 engineers were asked to evaluate their potential impact on the sustainability performance of the product system through focus groups.

4) *Validation*

Product development experts at the case companies were asked to review and discuss the proposed final criteria and proposed prioritization. Additionally, the LCA-based socio-ecological criteria were compared with previous criteria developed for the aerospace sector from a strategic, backcasting perspective and evaluated the commonalities and differences from a strategic sustainability perspective.

3. Results / Conclusions

This study developed a set of sustainability criteria based on literature and input from sustainability practitioners at two aerospace companies. These criteria can be used in requirements setting or as product development targets that can be used throughout the product development project and to manage the product development project portfolio at aerospace companies. It provides a clear, data-based prioritization through the use of LCA and Social LCA data and initially validates the framework through focus groups at the case companies. This framework provides clear guidance for sustainability-related trade-off management and helps design teams to effectively use their time to address the most impactful sustainability challenges.

Eco-Efficiency Assessment of Hydrogen Aircraft APU Maintenance Strategies: Integrating Economic and Environmental Criteria

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1. Introduction / Objectives

The aviation industry's pursuit of decarbonization has driven substantial investment into novel propulsion technologies, with liquid hydrogen emerging as a promising pathway toward climate neutral aviation. Yet as these technologies move closer to realization, a critical question arises: whether the lifecycle sustainability gains anticipated from hydrogen propulsion are genuinely achieved, or whether environmental and economic burdens are simply redistributed into the maintenance phase. Maintenance, Repair and Overhaul

activities for conventional aircraft already constitute up to a quarter of direct operating expenses, and with hydrogen hybrid systems introducing greater technical complexity, these costs and their environmental implications are expected to grow further. Despite this, existing assessments treat economic and environmental dimensions in isolation, limiting their practical value for industry decision making. This study addresses that gap by developing a combined eco-efficiency assessment framework for LH2 APU maintenance strategies, evaluated against a kerosene APU baseline, to support more informed and transparent investment decisions for next generation aircraft technologies.

2. Methodology

Building on the analytical baseline established by Meissner et al. , who demonstrated that scheduled preventive maintenance for a hydrogen hybrid APU entails measurable economic and environmental implications, this work takes the next logical step toward an integrated eco-efficiency perspective. Their parallel assessment revealed that both dimensions respond consistently to the same operational drivers, suggesting that a unified metric may provide additional decision-relevant insights. To explore this, predictive maintenance strategy is introduced alongside the existing scheduled preventive approach for the same LH_2 APU system, with task intervals derived from physics-based degradation models developed within the KlioWaLH_2 project and adapted into LYFE[2] to ensure a controlled, like-for-like comparison under identical boundary conditions.
To address the core research gap, a combined multi-criteria eco-efficiency framework is developed, integrating economic (e.g: maintenance man-hours per 1,000 flight hours) and environmental criteria (e.g: CO_2-equivalents per 1,000 flight hours, per ISO 14040/44) into a unified evaluation structure. This is benchmarked against established combination approaches from analogous industries to contextualize aggregation choices. The combined framework is then contrasted with parallel assessment to examine whether CBM offers a measurable eco-efficiency advantage for LH_2 systems, and whether integration surfaces decision relevant insights around technology investment viability that parallel assessment inherently conceals.

3. Results / Conclusions

This study is expected to demonstrate that the choice of maintenance strategy preventive versus predictive carries measurable eco-efficiency implications for LH_2 APU systems, with predictive maintenance anticipated to reduce both economic burden and environmental footprint relative to the preventive baseline. More critically, the comparison between the combined multi-criteria framework and the parallel assessment is expected to reveal that integration surfaces trade-offs and investment signals that remain hidden when economic and environmental dimensions are evaluated independently. These findings aim to provide industry stakeholders with a more transparent and actionable basis for decision making around LH_2 MRO technology adoption. Ultimately, this work contributes a transferable eco-efficiency assessment methodology applicable beyond the LH_2 APU use case, supporting broader efforts toward environmentally viable and economically sustainable lifetime services for next generation aircraft technologies.

Value-driven decision-making methodology to identify the best cargo door latching mechanism considering performance, supply chain, sustainability and reliability criteria at the same time

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1. Introduction

Designing modern aircraft has become much more challenging and complicated, meaning that aerospace engineers should take into account various aspects among different domains beyond structural and aerodynamic performance. By considering only aspects related with those domains, the evaluation would risk leading to isolated decisions, however, incorporating additional aspects coming from different domains such as, the supply chain, safety, environment and others, provides a more holistic basis for comparing alternative configurations of the same system. Conventional design approaches lack the ability to capture these cross-domain interactions, leading to costly system redesigns. In turn, this creates a need for a comprehensive multi-criteria design methodology that covers multiple aspects of the system's lifecycle from the earliest stages . This work aims at contributing to this change by enabling more holistic and robust decision-making during the design of nowadays aeronautical systems.

2.Methodology

In this context, a multi-criteria decision-making methodology is developed, that integrates aspects from four different domains during the design stage: Supply Chain, Sustainability, Reliability and Performance. For each of the previous aforementioned domains some Key Performance Indicators (KPIs), also called attributes, are identified and assessed: Cost, Time, Risk, Quality, Sustainability Factor, Reliability Index and Mass. Each KPI captures a critical dimension of the analysis scope. To evaluate such KPIs, a systematic methodology, based on a value-model is developed. This methodology formalizes a procedure on how to estimate each of these KPIs (details will be in the final paper). Once each KPI is estimated, the Multi Attribute Utility Theory (MAUT) is implemented for the aggregation of the various KPIs into a single value . For the application of such theory, a Utility Function is created and assigned to each KPI in order to quantify the stakeholders' preferences. In addition, a specific weight is assigned to each attribute, to represent the relative importance among them. The Cost KPI is treated as an independent variable. Therefore, the main outcome of the methodology is a value-cost tradespace in which several and interesting trade-off studies can be addressed by considering decision-makers´ expectations. The solution with the highest value can be assumed as the best architecture in terms of all the aggregated KPIs. In the current work, the System of Interest (SoI), i.e. the system under design, is a latching mechanism of the lower deck cargo door of an aircraft. Its main function is either to keep the lower deck cargo door closed and locked during the take-off, cruise or landing phase, or opened and locked during the loading or unloading phase of the cargo. Three already developed and distinct architectures of this SoI are evaluated based on the proposed multi-criteria methodology: Hook-Spool Latch Mechanism (HSLM), Bar Latch Mechanism (BLM) and C-Latch Mechanism (CLM). The main differences among such architectures are mainly the manufacturing cost, mass as well as the number of components that they are composed of. The objective is therefore to identify the

best latching mechanism architecture by considering all the mentioned KPIs.

3.Results and Conclusions

A preliminary outcome of the performed analysis is provided in **Error! Reference source not found.**. The presented Value vs. Cost trade-space reflects the use of linear utility functions and equal weights for all KPIs, ensuring that no expectations or preferences are introduced. The trade-space highlights how the best solution (the one with highest value) is the alternative 1-IH. This solution refers to the BLM architecture where all the components have been produced and assembled fully by an Original Equipment Manufacturer (100% In House). However, make or buy trade-offs can be performed among the solutions. According to the trade-space, the solution with the lowest cost is the alternative 10-O, which also indicates lower value compared to the aforementioned best solution (1-IH). The 10-O alternative refers to the CLM architecture where all the components have been produced by a supplier (100% outsourced), but the final assembly has been performed by the Original Equipment Manufacturer.

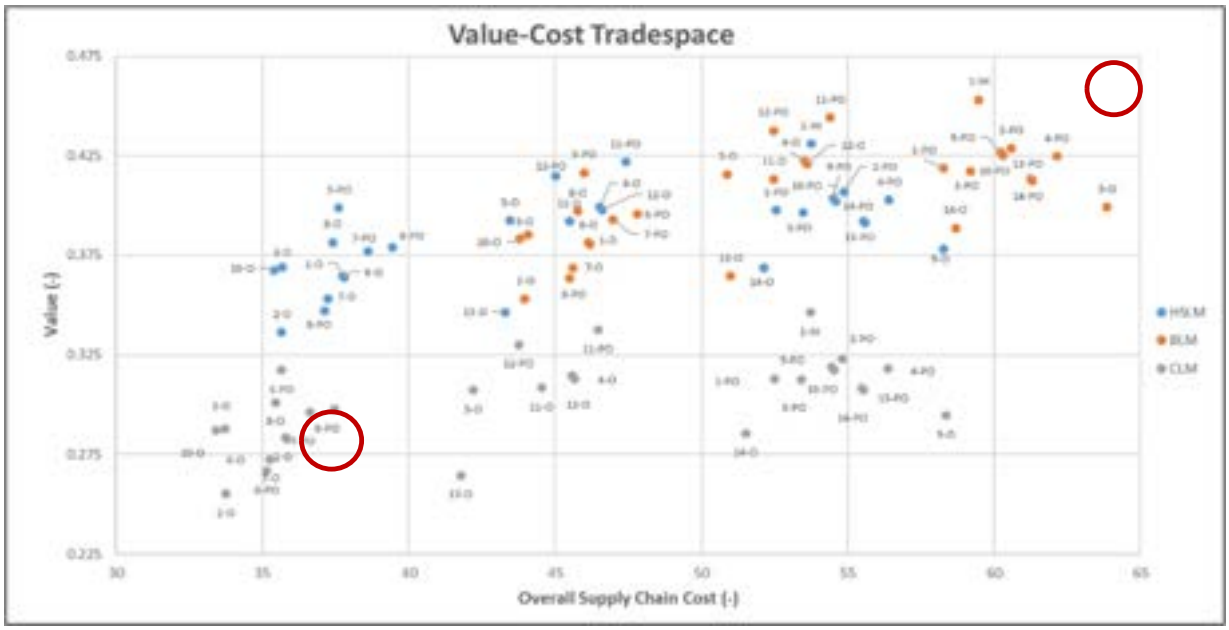


Figure 1. *Analysis preliminary results: Value VS. Cost trade-space*

Assessing Social Impact for Sustainable Aircraft Design through an SLCA Framework

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1. Introduction / Objectives

Within the social pillar of sustainability, Social Impact Assessment (SIA), or Social Life Cycle Assessment (SLCA), play a vital role across various sectors, and is established method in the mining industry, engineering project management, and in the assessment and comparison of

technologies. Furthermore, SIA is crucial for assessing the social impacts of large-scale transportation infrastructure, as well as broader national transport systems. The social dimension of sustainability is increasingly recognized as essential to the aviation sector, yet systematic assessment of social impacts across aircraft systems and their associated design and production processes remains limited.

2. Methodology

The proposed study applies Social Life Cycle Assessment principles, guided by the UNEP/SETAC guidelines and the ISO 14075:2024 standard, to perform a country-based screening that identifies, quantifies, and analyses hotspot impacts associated with materials production and manufacturing in the aviation sector. A tailored SLCA framework is developed to reflect the specific characteristics of the aviation sector and to identify relevant stakeholder groups, including workers, local communities, consumers, value chain actors, and society. Moreover, aviation-specific social indicators are defined in line with industry needs and regulatory expectations, enabling socially informed decision-making during early design stages.

The methodology is demonstrated through a comparative screening assessment between Airbus A350-900 (Figure 1), which aligns with the reference aircraft defined in the EXAELIA project , and a comparable wide-body aircraft, examining social impacts across global supply chains, identifying social hotspots and country-specific risk drivers, and evaluating targeted improvement measures.

3. Results / Conclusions

The findings, expressed as the number of social hotspots per aircraft subsystem, provide actionable insights for policymakers and industry stakeholders and support holistic sustainability assessments by explicitly integrating the social dimension into sustainable aircraft design. Within the framework of the EXAELIA project, the proposed study enables a meaningful SLCA first-screening comparison between the developed aircraft configurations and the reference aircraft.

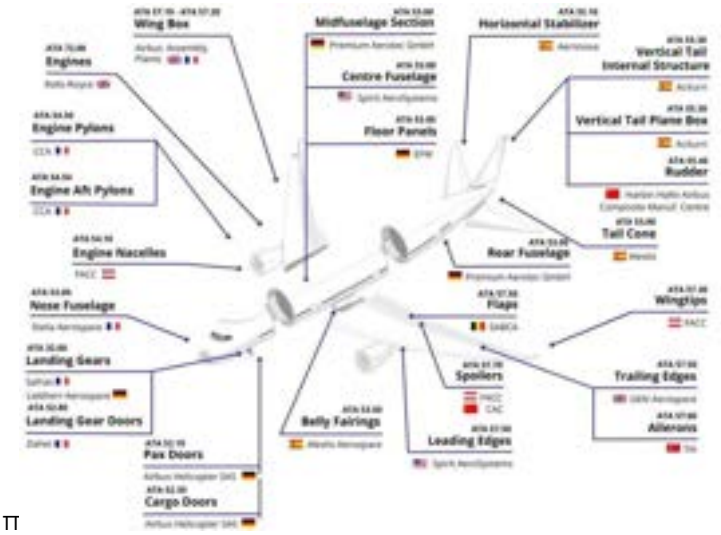


Figure 1. *Overview of the Airbus A350-900 subsystem and corresponding suppliers.*

Acknowledgment: The present work is being funded by the European Union under GA No. 101191922 (EXAELIA). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Material Selection for 3D-Printed CubeSat Structural Subsystems Using a Holistic Sustainability Assessment Framework

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1. Introduction / Objectives

CubeSats have widened access to space, but their fast growth has also raised new sustainability concerns for the space sector. These concerns are usually discussed at mission or orbital level, while the effect of early engineering choices at subsystem level is often overlooked. This work focuses on CubeSat structural subsystems and proposes a material selection framework toward sustainability assessment framework for early design stages. The aim is to evaluate the applicability of 3d printed materials by combining technical requirements with broader sustainability criteria, adapted to the needs and constraints of space engineering.

2. Methodology

The proposed methodology develops a sustainability assessment framework for the early design of CubeSat structural subsystems, when different concepts and material options can still be compared. The approach combines standard structural design criteria with sustainability-related criteria in a single evaluation process. From the engineering side, the framework considers mass, mechanical performance at different levels, and compliance with CubeSat design constraints. These parameters ensure that the structural solution remains technically feasible and aligned with mission requirements. From the broader sustainability side, the framework is organized around environmental impact, circularity potential, and economic aspects, using metrics adapted to the space sector. The process follows four steps. First, the structural subsystem is defined within the CubeSat architecture, together with its main functions and constraints. Second, candidate design options are described through proposing different 3d printing materials for incorporation to the . Third, evaluation criteria are weighted according different mission priorities and design objectives. Fourth, the alternatives are compared through a scoring process to identify key trade-offs and preferred solutions. The framework is not intended to replace conventional structural selection methods but showcase the introduction of holistic sustainability as a design parameter from the conceptual design phase.

3. Results / Conclusions

The proposed framework demonstrates the evaluation of selection of 3D-printed materials for CubeSat structural subsystems though a holistic sustainability method. This enables a clearer comparison between candidate 3D-printed materials and makes early-stage sustainability trade-offs visible. Overall, the work contributes to the use of additive manufacturing in space structural design by introducing sustainability as an explicit material-selection criterion.

Air Traffic Management (ATM) and Airports Subjects

Chaired by:
Prof. Octavian Thor Pleter (University Politehnica of Bucharest, Romania)

Design and Integration of an AI-Based ATC Communicator within a Digital Co-Pilot for Single Pilot Operations

Yasir Mahmood Khan, Marko Radanović
Pipistrel Italia, Italy

1. Introduction

For more than a century, communications between the pilots and air traffic control (ATC) have ensured the traffic safety and situational awareness maintained. It had evolved from early radio to modern voice procedures . The increasing airspace complexity due to air traffic growth and new operational concepts presents challenges to safety and efficiency. In response, one of the SESAR visions for the Digital European Sky aims at creating highly automated cockpit functions for the airspace users pillar within air traffic management ecosystem . Within this framework, the DARWIN (Digital Assistants for Reducing Workload and Increasing collaboratioN) project introduces an AI-based Digital Co-Pilot concept. One of the key innovative modules in DARWIN is the ATC Communicator, which aims to integrate an automated decision support with the conventional voice-based ATC communication . The ATC Communicator enables automated aircraft-to-ATC communication. Current ATC communication relies mostly on voice exchanges, while the controller-pilot data link communication (CPDLC) introduces structured but limited text messaging. This work addresses the need for communication support under high workload conditions encountered during single pilot operations (SPO) in the en-route cruise phase of flight. The paper presents a novel approach where AI-based operational messages, synthetically generated as inputs, are automatically converted into speech and transmitted via VHF radio, enabling integration of automated decision-making by the digital co-pilot into existing ATC voice communication practices without requiring infrastructure changes.

2. Methodology

The DARWIN solution is built around the Introductory Digital Co-Pilot (IDCP), which integrates multiple technical and human-centric enablers to support pilot decision-making while maintaining human-in-the-loop operation. The IDCP operates at EASA Level 2B automation , corresponding to supervised automated decision-making and execution. The system incorporates the following relevant enablers:

1. Trustworthy Machine Reasoning Platform (TMRP): Provides transparent, rule-based decision-making using explainable AI techniques
2. Human-AI Teaming (HAT): Hardware to manage task allocation between pilot and automation while ensuring pilot oversight

3. Monitors: Pilot State Monitor (PSM), detecting pilot drowsiness, sleep, and incapacitation, and Task Load Monitor (TLM), estimating current and predicted pilot workload based on operational context
4. Human: Training for pilots to interact with the digital co-pilot

Within this ecosystem, the ATC Communicator is implemented as one of the key assistants under the HAT enabler. It is responsible for transmitting relevant outputs generated by other IDCP modules to ATC. The operational workflow of the ATC Communicator is defined as follows:

- Detection of an operational event or advisory by the PSM and TLM
- Decision support logic executed through the TMRP
- Task allocation and validation through the HAT system and structured communication content
- Conversion of structured content into standard aviation phraseology
- Text-to-Speech (TTS) conversion into natural voice output
- Transmission of the voice message using the aircraft intercom and VHF radio system

This approach differs fundamentally from CPDLC by preserving the voice-based communication channel, ensuring compatibility with current ATC operations. The ATC Communicator operates under strict safety constraints, including:

- Pilot supervision and override capability and integration with task allocation logic from HAT
- Use of validated outputs from TMRP to ensure explainability and traceability

The complete system has been developed and validated as part of the IDCP prototype, reaching TRL6 maturity, including integration into the Pipistrel Panthera CS-23 aircraft for the realistic operational testing.

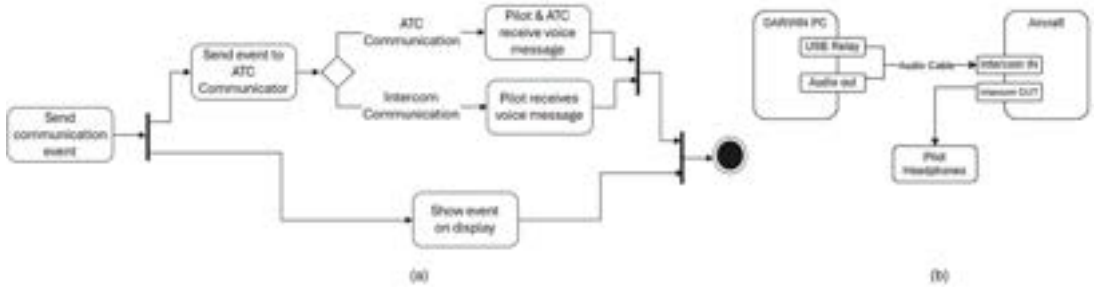


Figure 1. *(a) ATC Communicator flow diagram;(b) ATC Communicator interface with the aircraft*

3. Results / Conclusions

The DARWIN IDCP, including the ATC Communicator, was validated through both TRL4 (simulation-based) and TRL6 (flight-based) exercises. The TRL6 validation involved eight flight tests using the Pipistrel Panthera aircraft under normal and abnormal operational scenarios, including pilot incapacitation and emergency situations. Results demonstrate that the ATC Communicator successfully enabled automated transmission of AI-generated messages via standard ATC voice channels, maintaining operational compatibility. Feedback from

participating pilots confirmed that the ATC Communicator helped reduce workload, particularly in high-demand situations, without increasing cognitive burden. The integration with other IDCP assistants and monitors ensured context-aware communication triggered by real operational needs. The overall system met all validation objectives, confirming feasibility of Level 2B automation. The study concludes that AI-driven voice-based ATC communication represents a viable and novel solution for future SPO operations, supporting safe and efficient integration of automation into existing ATM framework.

Experiments with a Low-Cost True North Heading Sensor for General Aviation

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1. Introduction / Objectives

ICAO established the True North Advisory Group (True-AG) with the objective of assisting ICAO in developing a framework for a safe and efficient global transition to True North, developing a CONOPS and transition plan, and providing strategic advice to ICAO . IMO took a similar decision in 2000 for the maritime industry. The AIS transponder for ships sends two directional parameters, both in True: Track and Heading, equal most of the time, when the ship is on the move. The challenge in aviation is the prohibitive cost of the IRS. GNSS delivers the True North track, but in contrast with the maritime case, the wind generates a drift angle between the heading and the track. General Aviation (GA) is reluctant to accept the transition in the absence of a True heading low-cost sensor . This research aims at experimenting with an RTK dual antenna GNSS receiver capable of delivering True heading at a low cost.

2. Methodology

The experiments on which the paper is based were carried out with an RTK dual antenna GNSS receiver. In General Aviation, the current requirements for a heading sensor concern Magnetic North, so there is no low-cost True North heading sensor available on the market. Searching for a low-cost such sensor, we found the UM982 RTK receiver, supplied by Unicore, currently in use for terrestrial vehicles. The True North track is delivered by the sensor, by differentiating the successive positions. The True North heading is measured by the phase difference between two antennas placed at a minimum distance of 1 m between them. The methodology was to assess the accuracy and the consistency of the True heading measurements under various meteorological conditions, time of day, satellite availability, etc. The experiments in the first phase were carried out on a car because of the absence of the drift angle. In the second phase, we installed the sensors on a Robinson R44 helicopter. The helicopter presents a special challenge to the True North transition because, like ships at anchor, during the hover manoeuvre, there is no track defined, and the position does not change. In the experiments, besides accuracy, we sought to quantify integrity, availability, and continuity. Some experiments were done in the Danube Delta region, which is often affected by GPS spoofing and jamming.
The accuracy of the algorithm to determine the True heading decreases when the pair of antennas loses its horizontality. For terrestrial vehicles, this is rarely an issue, and for that reason, the software of the receiver does not address this problem. For an aircraft, the attitude angles may change significantly in flight, altering the projection of the base between the two antennas in the direction to each satellite. The authors enhanced this

algorithm with a correction of the heading with the pitch angle, which would be required for a flying vehicle. The experiments to validate this algorithm were carried out with the two antennas installed on a common pitching platform.
For the helicopter experiments, the difference between the True heading and the Magnetic heading in hovering was compared to the known magnetic compass variation.

3. Results / Conclusions

The experiments in this research indicate a good potential for a low-cost True heading sensor based on GNSS RTK with two antennas. A GA aircraft employs a GNSS sensor anyway for navigation, so the upgrade to a twin antenna setup is not a problem, and upgrading the receiver will come with the added benefit of multi-constellation resilience to jamming and spoofing, which are frequent in some areas.
The accuracy of the True heading sensor is at 0.1°, exceeding the accuracy of a typical GA magnetic compass. The total cost of the parts required for the True heading set-up was below €200, justifying this solution as a low-cost one.

The main conclusion is that there is a low-cost True heading sensor for GA, as this paper demonstrated. The helicopter experiments validated the feasibility of the use of the receiver in an aircraft.

GRAPH-DECIDE: A Graph-Based, Multi-Criteria Decision-Support Framework for Air Traffic Management under Delay and Capacity Uncertainty

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1. Introduction / Objectives

Reactionary delays and capacity-driven disruption dominate the residual cost of European Air Traffic Management (ATM): regulations propagate non-linearly along shared capacity, rotations and arrival streams . Existing tools forecast per-flight delay but treat the *decision* (hold, reroute, absorb, swap) as a downstream consequence rather than the object to be optimised . GRAPH-DECIDE, a 12-month SESAR Engage 2 Catalyst project, places operational decisions at the centre of modelling and learning. The objectives are threefold: (i) a formal graph in which flights, sectors, TMAs, airports, ATFM regulations and candidate decisions are first-class nodes; (ii) a Graph Convolutional Neural Network (GCNN) that ranks decisions by expected network-wide impact under multi-criteria objectives; and (iii) a validation protocol with airline and airport stakeholders scoring decision *quality* (reactionary-delay reduction, demand–capacity stability, robustness) over prediction accuracy alone. GRAPH-DECIDE addresses Engage 2 Thematic Challenge 3 and targets Dynamo3 for higher-TRL maturation.

2. Methodology

The work is organised in four phases, from formal modelling to validated decision support.
Phase I — Data and graph construction. The base dataset is the Eurocontrol ADRR R&D

release for March 2023 (~682 k flights across the EUROCONTROL Network Manager area), extended with the per-flight Flight-AUA and Flight-FIR traversal tables that ship in the same bundle and with OPDI v2.0.0 ADS-B trajectory milestones . Additional sample months across 2015–2023, released to OneSky R&D users at four months per year, broaden the training window. Per-flight ATFM cause attribution is the remaining open data item; candidate sources are a STATFOR custom extract, DDR2 and NM B2B Flow services, pursued in that order. The graph stores flights, airspace sectors and TMAs, airports, ATFM regulations and explicit decision nodes, connected by four edge families: *causal* (reactionary propagation), *capacity coupling* (shared AUA traversal or arrival stream), *temporal succession* (previous/next rotation of the same tail, derivable from `AC Registration` and actual off-block time) and *decision impact* (decision → expected cost/delay). Attributes carry delay causes, expected holding, capacity limits, time-dependent cost functions and uncertainty indicators.

Phase II — Graph database and tensor export. The graph is materialised in Sparksee 6 , built from scratch; no Sparksee deployment is inherited from the Travel Wise project, whose Disruption Knowledge Model is reused as a *structural* reference only. A Python connector walks Sparksee subgraphs and emits PyTorch Geometric `Data` objects in memory , so the GCNN trains directly on the operational graph.
Phase III — Model and baselines. A 3-layer GCNN is trained on static graph snapshots, with a temporal extension (T-GCN / TGN) held in reserve if static performance plateaus. It is benchmarked against a CNN baseline that treats the network as a grid of airport-hour cells; the configuration is designed to outperform on *decision relevance*, not aggregate delay error. A multi-criteria decision head ranks actions over four objectives: fuel cost, on-time performance (≤15 min), passenger disruption and reactionary delay risk. The weighting scheme is itself a deliverable, elicited through structured stakeholder consultation rather than fixed a priori.
Phase IV — Validation. Realistic disruption scenarios (sector capacity reductions, en-route regulations, hub weather closures) are drawn from held ADRR/OPDI months and synthetic perturbations seeded from the same distributions. Decision rankings are reviewed by airline and airport experts for usefulness, interpretability and trust; quantitative indicators (reactionary-delay reduction, demand–capacity stability, decision robustness) accompany the qualitative review.

3. Expected Results / Conclusions

Within twelve months, GRAPH-DECIDE will deliver: (a) a published formal graph model for operational ATM decision support, including the decision-node and decision-impact-edge schema absent from prior delay-prediction graphs; (b) a Sparksee-backed prototype with a GCNN that outperforms a CNN baseline on a defined decision-relevance metric, with rankings explainable at node and edge level; (c) a validated use case on realistic disruption scenarios, reviewed with airline and airport stakeholders; and (d) a maturation roadmap for higher-TRL SESAR research, including a possible Dynamo3 integration path. Known risks are the per-flight ATFM cause attribution gap and the absence of historical decision–outcome pairs in public European data; both are tracked openly, and the validation protocol accepts synthetic decision scenarios where the record is silent. By shifting the optimisation target from delay metrics to decision quality, GRAPH-DECIDE contributes a graph-native, explainable building block to the SESAR vision of performance-driven, human-centric ATM.
This work is developed by Sparsity Technologies and collaborating partners under a SESAR Engage 2 Catalyst grant, with the SESAR Joint Undertaking and the European Commission as

co-founders. It builds on the Disruption Knowledge Model defined in the Travel Wise project and extends it from delay analysis toward decision optimisation.

Aggregated metrics for the evaluation of ATM efficiency

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1. Introduction

Air Traffic Management (ATM) is a critical component of the European air transport system; its efficiency significantly impacts the airlines' profitability and is also a lever of air transport decarbonization, with an expected overall contribution up to 8% in the reduction of aviation-related emissions between now and 2050. In this perspective, the presented work develops a methodology to quantify and question the potential of ATM efficiency gain. This work details how a compound ATM efficiency metric can be defined starting from the weighted aggregation of local efficiency indicators, which are quantifiers of horizontal or vertical efficiency at different flight phases, or from a fuel consumption model applied to the real ADS-B trajectory. The computation of the metric is robust and can be applied to short- and long-haul flights alike, enabling the analysis to be applied to a single flight, to a given commercial airline network and over large geographical air spaces, as far as flight plans and trajectories are available.

2. Methodology

A detailed review of the existing literature revealed that most studies on operational and Air Traffic Management (ATM) efficiency are limited either to a single flight phase or to specific geographic scopes. This research aims to develop a generalized and robust framework capable of assessing the operational efficiency of airline trajectories under realistic ATM constraints. As such, it does not aim to measure the potential efficiency gains from alleviating the current constraints, inherited from decades of ATM design and implementation. The methodology combines several complementary indicators describing both horizontal and vertical flight performance throughout the different phases of flight.

The first indicator, Distance Efficiency, evaluates the horizontal trajectory performance by comparing the actual en-route flown distance with the shortest filed en-route distance on the same city pair. To avoid terminal-area distortions, circles of 40 NM around both departure and arrival airports are excluded from the computation. A second metric, Hold Distance, quantifies inefficiencies related to airborne holding patterns and additional path extensions during the arrival phase.

Vertical performance is characterized using three additional indicators. The Climb (or Descent) Flight Path Angle compares the executed trajectories with reference climb (or descent) profiles, which serve as proxies for optimal operations despite uncertainties related to aircraft mass and operational conditions. In parallel, Vertical Flight Efficiency (VFE) follows the definition proposed by EUROCONTROL , measuring the share of cruise distance flown at an altitude greater than 1,000 ft below the level declared in the latest pre-departure flight plan.

To ensure comparability, all the local metrics are normalized and recentered at 1, with above one values indicating increasing inefficiency and below one indicating increased efficiency. The aggregated operational efficiency index is then computed as the product of the individual indicators, providing a synthetic assessment of flight performance. Several weighting strategies are currently being investigated to refine the aggregation methodology. Additionally, a parallel fuel-based efficiency metric is introduced to account for the unequal operational impact of inefficiencies across different flight phases, which, for example, affects significantly flights that incur in holding patterns. The metric can be detailed to single phases and compares the real flight segment consumption to a reference one, defined considering ATM constraints (buildup of best constrained trajectory per phase). Figure 1 presents the distribution of the fuel-based efficiency metric across nine airport pairs, representative of Europe-based operations, with each flight direction analyzed separately. An indicator value greater than 1 signifies that the actual fuel consumption exceeds the reference consumption proportionally. Assuming that all flights exhibiting an indicator above 1 could be optimized to match the reference trajectory, the resulting efficiency improvement in this subset of the European network would correspond to an estimated gain of 9%.

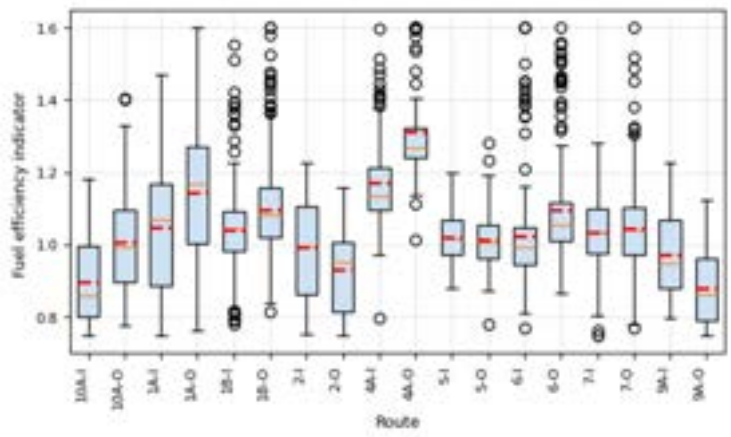


Figure 1. *Boxplot of the aggregated fuel efficiency metric for 9 different airport pairs, with at least one end in Europe; each route is characterized by an alphanumeric code and O/I (Outbound, Inbound) for the direction.*

3. Conclusions

This study proposes a unified framework for assessing airlines operational efficiency in an ATM constrained environment by integrating complementary horizontal and vertical flight performance indicators. By moving beyond single-phase analyses to the evaluation of the entire flight, the approach enables a comprehensive evaluation of the potential reduction of climate impact thanks to improved operations. The task is particularly challenging because the operational constraints are difficult to generalize and systematically categorize when past operations are post processed. Nonetheless, aggregating normalized metrics into a single efficiency index enables consistent flight comparisons while retaining insight into individual inefficiency sources. The introduction of a parallel fuel-based indicator further enhances the framework by capturing the unequal operational and environmental impact of deviations across flight phases. At this stage, results confirm the magnitude of the contribution of improved operations to the decarbonization of aviation. The analysis will be

enhanced using a broader dataset and with the analysis of uncertainties, due to the aircraft performance models and initial mass assumptions used in the computation.

Predicting Go-Around Likelihood: Towards the Development of an EASA-Compliant AI-Based Decision Support System

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1. Introduction / Objectives

In approach and landing operations, go-arounds are safety-critical events, associated with elevated crew workload and adverse operational conditions. This pressure is amplified by a projected shortage of nearly 700,000 pilots by 2043 , placing crews in high-stress situations and making automated decision support a strategic necessity. Historical ADS-B data allows analyzing such events at scale, motivating the scalable, open-data pipeline presented in this work. We introduce Gorald, a go-around likelihood predictor for flight crew decision support. Gorald fuses heterogeneous real-world sources—ADS-B trajectories and METAR weather observations—into a homogeneous, ML-ready dataset, addressing challenges including label imbalance and heuristic labeling. Gorald achieves a PR-AUC of 0.958, substantially outperforming a Logistic Regression baseline (PR-AUC: 0.818).

2. Methodology

This work addresses a Level 1B human cognitive assistance application as defined in the EASA concept paper , targeting flight crew decision support by predicting go-around likelihood during the final approach phase. The Operational Design Domain (ODD) covers commercial fixed-wing operations at Hamburg Airport across all weather conditions. ADS-B trajectory data was sourced from OpenSky Network's historical Trino database for its comprehensive coverage. Raw data was filtered to commercial traffic via a callsign whitelist, excluding private, rescue, and police flights. Meteorological observations from METAR reports were mapped to approach events using a nearest-neighbor timestamp lookup within a 30-minute window. This integrated two heterogeneous sources into a homogeneous, ML-ready dataset, satisfying EASA Objective DM-01 . Go-around events were identified by detecting descent-to-climb reversals based on vertical rate, altitude gain within 15 seconds, distance from the airport reference point, and velocity dip as a TO/GA signature. Key challenges included erroneous on-ground flags, ambiguous touch-and-gos, and incomplete tracks. Features extracted per approach include descent rates, speed stability, glide slope and lateral deviations, heading changes, duration, and matched weather parameters (wind speed, visibility, ceiling height), resulting in 27 features in accordance with EASA Objective DM-04 . To process these features under conditions of severe class imbalance, an XGBoost classifier was selected as the primary model, using *scale_pos_weight*, compared against a Logistic Regression baseline. The dataset was split 60/20/20 using stratified sampling. Model performance was evaluated using precision, recall, F1-score, and PR-AUC. The complete data processing pipeline is illustrated in Figure 1.

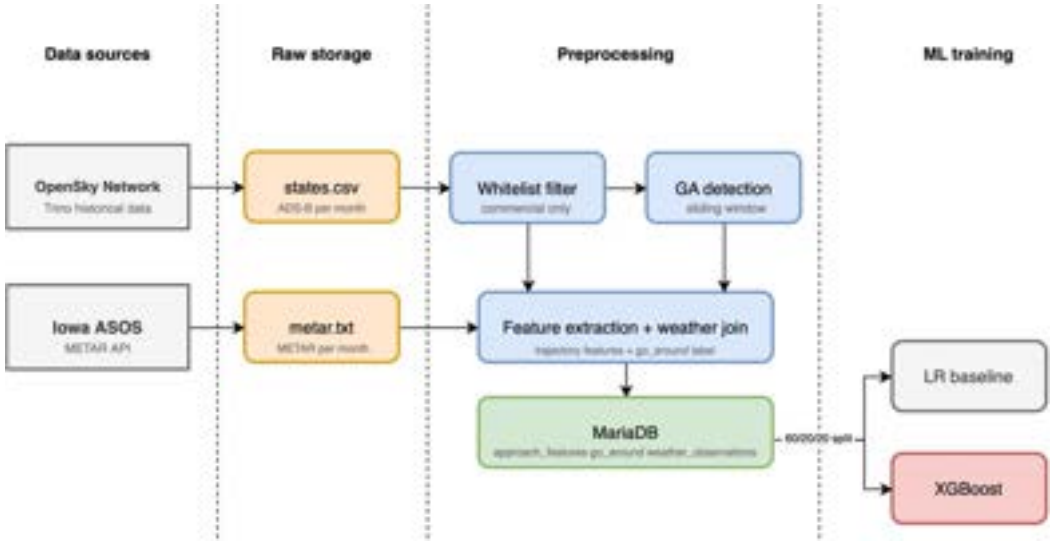


Figure 1. *End-to-end data pipeline from raw ADS-B and METAR sources through go-around detection and feature extraction to the final ML-ready dataset.*

3. Results / Conclusions

Across 20,189 filtered landings, 87 go-around events were identified, yielding a class imbalance ratio of 1:231. The XGBoost classifier achieved a precision of 0.938, a recall of 0.882, and an F1-score of 0.909 on the held-out test set. The PR-AUC of 0.958 substantially outperforms the Logistic Regression baseline (F1-score: 0.696, PR-AUC: 0.818), confirming non-linear feature interactions among go-around precursors and fulfilling Objective IMP-08 . Average descent rate, approach duration, descent rate variability, and position update frequency were identified as the strongest predictors, with further objectives addressed in the full paper. These results represent a concrete step toward a certifiable AI/ML constituent for the development of EASA-compliant crew decision-aid tools.

Improved Aircraft Protection on Ground Through Heterogeneous Sensor Fusion: an Experimental Assessment

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1. Introduction

Airport ground operations remain among the most safety-critical phases of flight, as runway incursions, vehicle intrusions, and close-proximity events can quickly escalate into damage or loss of separation . The SESAR Exploratory Research project Alternate Surveillance Technologies fOr iNnovatIve Solutions (ASTONISH) investigates how heterogeneous sensing technologies can enhance situational awareness on the airport surface.
This abstract presents an experimental assessment carried out at the ATLAS facility owned by CATEC in Spain, in an operational scenario featuring an ultralight aircraft and a car. The objective is to evaluate and compare different sensing architectures (or modalities): a stereoscopic camera system, a lidar-based setup, and two radar-plus-camera configurations. The innovation lies in validating sensor performance not only individually, but also through their fusion, showing how complementary sensing modalities improve robustness.

2. Methodology

The experimental campaign was carried out at the ATLAS BRAVO facility owned by CATEC in Spain. The facility comprises two runways, 800 and 1500 meters long. The test environment reproduced interactions between an ultralight aircraft and up to three cars (see Figure 1 – a), with emphasis on use cases in which the vehicle intruded into the protected operational area of the aircraft (runway or taxiway). The acquisitions were organized to capture dynamic phases, thus enabling the evaluation of target detection, localization under realistic line-of-sight and proximity conditions at the same moment for the three sensing configurations.



Figure 1. *A test involving two cars with onboard sensors following the aircraft and one car incursion on the runway (a). Test setups includes stereoscopic camera (b) LiDARs (c) radars (d-e)*

The first setup (Figure 1 – b) relied on a stereoscopic camera system, used to extract object and depth-aware position estimates from synchronized image pairs. A specific AI model based on a Deep Learning approach, has been trained on custom airport data for semantic interpretation and target classification.
The second setup (Figure 1 – c) employed lidar, which provided dense 3D point cloud measurements of the scene. Semantic segmentation was applied through a trained deep

learning model, assigning each point to an operationally relevant category, including vehicles, aircraft, persons, and infrastructure, enabling scene-level interpretation of the airport surface.
The last setup (Figure 1 – d-e) combined radars and cameras, exploiting the former for robust detection of moving objects and the latter for visual confirmation and contextual interpretation. Radar measurements were processed through a strategy designed to identify targets of interest and mitigate clutter.
For all setups, the processing chain included synchronization over a common operational timeline. The three configurations were then compared against the same use cases, with particular attention to runway-incursion-like trajectories generated by the car in proximity to the ultralight aircraft.

3. Results and Conclusions

The results show that the three sensing modalities provide distinct but complementary information. The stereoscopic camera offers strong semantic interpretation, the lidar provides accurate 3D context and operates independently of lightning conditions, and the radar adds robustness and continuity in dynamic conditions through accurate position and radial velocity measurements. However, each sensor also exhibits modality-specific limitations, including occlusions, clutter, and intermittent visibility. The fused outputs improve overall detection continuity and recovering targets that are missed or only partially observed by individual sensors. These findings confirm that heterogeneous data fusion is a promising approach for improving aircraft protection on ground and support future development of multimodal airport-surface surveillance systems.

Acknowledgement: This research is carried out in the framework of the SESAR ASTONISH project, supported by the SESAR 3 Joint Undertaking and its members under grant agreement No 101167383 under European Union's Horizon Europe research and innovation programme. Funded by the European Union. Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or SESAR JU. Neither the European Union nor the granting authority can be held responsible for them.

Proposal of an enhanced qualitative safety assessment framework for A-to-A HTOL suborbital operations in ATM using a EUROCONTROL-based risk modelling

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1. Introduction

The development of new concepts of operations for suborbital space vehicles transiting through European Air Traffic Management (ATM) and operating at High Altitudes (HA) has led on the one hand to ask for significant progress of technologies to ensure the safe, efficient, and interoperable integration of these new entrants into airspace operations, on the other hand to define innovative mechanisms and procedures for the ATM. The approach adopted so far by Civil Aviation Authorities (CAAs) requires to segregate large volumes of airspace for considerable periods of time to accommodate such vehicles in ATM, clearly causing delays and disruption to other airspace users. The expected increasing

demand for such missions over the next decade, makes this approach unfeasible already in the medium to long term, raising a challenge for a better use of airspace exploiting the flexibility introduced by a new concept of 4D dynamic volume operating zone implementation. Traditional airspace divided into fixed 3D blocks, i.e. latitude, longitude and altitude by adding the time dimension will allow these zones to change dynamically according to real conditions.
Such approach can pose risks to ATM management, but the application of current EUROCONTROL Integrated Risk Model is not fully adequate because no AIM (Accident Incident Model) associated to suborbital operations is available, and the impact of the change on the potential safety barriers and precursors cannot be referred to existing AIM models. Modifications or extensions of the existing model are needed to address the unique challenges posed by suborbital flights.

2. Methodology

This paper proposes a qualitative safety assessment for A-to-A Horizontal Take-Off and Landing (HTOL) suborbital operations, by integrating hazard identification, risk quantification, and evaluating the mitigation effectiveness. The approach is aligned with the SESAR Expanded Reference Material (E-SRM)[1] to ensure a safety assessment and assurance process through the different system lifecycle phases: definition, specification, and pre-industrial design phases.

3. Conclusions

Ansys MEDINI© software has been used for implementing the proposed methodology, resulting in a clear model for local safety case development, that can support Air Navigation Service Providers (ANSPs), airport authorities, and operators in evaluating the safety impact of suborbital operations and associated procedures, also optimizing barriers efficiency prior to operational deployment.

A Teamwork Assistant for Adaptive Human-AI Collaboration in Air Traffic Management: Findings from the DIALOG Project

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1. Introduction / Objectives

The increasing integration of Artificial Intelligence (AI) into Air Traffic Management (ATM) requires new approaches to Human-AI Teaming capable of supporting operators while preserving human authority, situational awareness, promoting trust and monitoring control in safety-critical environments. Existing ATM solutions mainly focus on task-specific support and often lack adaptive collaboration mechanisms based on the operator's intent, cognitive state, and the operational context. Within this framework, the DIALOG project investigates the feasibility of a collaborative AI-based Teamwork Assistant for en-route ATM operations. The proposed solution combines an Intent Inferring Service, processing pilot-controller communications to infer Air Traffic Controllers' (ATCOs) goals and operational intentions, with a Teammate Awareness Service, classifying workload and attention through multimodal behavioural and psychophysiological indicators. The main objective of the study is to explore the preliminary operational feasibility, human performance implications, and trust-related dynamics of adaptive Human-AI Teaming concepts at Technology Readiness Level 2 within realistic ATM operational scenarios.

2. Methodology

The study was conducted within the DIALOG SESAR Exploratory Research project through a Human-In-The-Loop simulation campaign involving licensed ATCOs interacting with the Teamwork Assistant in mimicked realistic en-route ATM scenarios. The validation focused on the integrated DIALOG Teamwork Assistant, combining the outputs of the Intent Inferring Service and the Teammate Awareness Service to provide adaptive operational support during tactical management of pilot requests, including level changes and weather-related clearances.

The validation activities were performed using a high-fidelity simulation environment reproducing operational characteristics of Marseille Area Control Centre en-route sectors. Controllers (N=10) performed scenarios simulating current operations both without the AI support (i.e. reference scenario) and with the Teamwork Assistant integration (i.e. solution scenario). In this latter, the Teamwork Assistant dynamically adapted its support logic according to operational context, inferred controller intent, workload estimation, and traffic conditions.

The methodological approach combined quantitative and qualitative data collection techniques to evaluate operational feasibility, usability, workload, trust, interaction fluency, and situational awareness. Data sources included system logs, subjective questionnaires,

semi-structured debriefing interviews, and multimodal psychophysiological measurements. Neurophysiological data collection included behavioural and physiological indicators aimed at exploring real-time assessment of operator cognitive state within ecological operational conditions.
The assessment framework focused on Human Performance aspects of collaborative Human-AI Teaming, including monitoring behaviours, trust calibration, explainability, perceived operational relevance, interaction coherence, and the effects of adaptive support strategies on operator performance. Particular emphasis was placed on understanding how adaptive automation can support controllers while preserving active human engagement in safety-critical operations. Comparative analyses between reference and solution conditions were conducted to explore differences in controller experience and operational interaction patterns. Consistent with the exploratory maturity level of the solution, the validation activities focused on feasibility, acceptability, and future research needs rather than on demonstrating definitive operational performance gains.

3. Results / Conclusions
Preliminary findings suggest that the DIALOG Teamwork Assistant was perceived as operationally relevant, consistent, and compatible with existing controller practices. The introduction of adaptive AI support did not negatively affect situational awareness, operator engagement, or workload during the simulations. Controllers consistently maintained active monitoring behaviours and frequently validated Teamwork Assistant outputs before implementation, indicating preservation of human authority and responsibility within the operational loop.
Qualitative feedback highlighted transparency, explainability, and predictability as important enablers of effective Human-AI Teaming. These characteristics supported positive perceptions of the Teamwork Assistant and appropriate trust calibration while preserving active human involvement in decision-making. Participants reported that adaptive support strategies could help manage workload peaks and facilitate collaboration with the AI assistant without reducing operator vigilance . Overall, the study provides preliminary evidence supporting the feasibility of collaborative Human-AI Teaming in ATM and highlights the importance of explainable adaptive support, calibrated trust, and meaningful human oversight in future AI-enabled operations.

Massive Cherry-Picking Multi-Objective Air Traffic Flow Management Through Lexicographic Optimisation, Trade-Offs, Analysis and Fine-tuning

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1. Introduction / Objectives
European Air Traffic Management (ATM) faces growing demand-capacity imbalances across a complex, interdependent network. Current Computer-Assisted Slot Allocation (CASA) addresses congestion through slot allocation based on fixed sector entry rates, but struggles to reconcile multiple stakeholder objectives simultaneously. The SESAR project HARMONIC introduced Lexiflow, a novel algorithm that optimises demand-capacity balance (DCB) problems via a multi-objective lexicographic approach at European Airspace Network Level. Unlike CASA, Lexiflow assigns Massive Cherry-Picked (MCP) delays, selecting the best flights to delay within configurable bounds, while respecting a priority-ordered set of objectives including optispot compliance, spike smoothing, delay minimization, and fuel

efficiency, introducing a new set of trade-offs. Complementary to this, the SESAR project ISLAND leverages machine learning to anticipate critical situations requiring network-wide resolution. Together, these innovations represent a paradigm shift in ATM automation, enabling systematic exploration of trade-offs between efficiency, fairness, and operational constraints.

2. Methodology

Lexiflow is formulated as a Mixed-Integer Linear Programming (MILP) problem solved via a lexicographic sequence of MIP sub-problems, each targeting a successively lower-priority objective while preserving higher-priority optimality within configurable tolerance bounds . A Flight Plan Alternatives Module draws from a route catalog compliant with the Route Availability Document (RAD) , expanding the solution space with rerouting options alongside ground delay assignments.

Airspace health is characterised through a Network State Indicator (NSI) framework classifying network conditions into three states: Nominal, Non-Nominal, and Critical, across defined Spots: Hotspots (local DCB imbalances), Optispots (optimisation opportunities), Coldspots (available absorption capacity), Protection Spots (congestion early warnings), and Netspots (network-level propagation of multiple imbalances).

Validation used EUROCONTROL's INNOVE real-time gaming platform . The PLANTA tool provided the human-machine interface reproducing the operational look-and-feel of the Network Manager's Operations Centre (NMOC). MILP problems were solved using the open-source SCIP and CBC solvers integrated in Lexiflow.

Latest iterations of the solver introduced a meta-optimization harness that systematically explores the configuration space, varying objective subsets, tolerance values, and maximum delay caps, and computes a Pareto front to identify non-dominated configurations. Parallel independent workers execute individual Lexiflow runs, enabling efficient trade-off analysis across competing objectives such as optispot compliance, delay spike smoothing, total delay minimization, and fuel consumption reduction.

The simulation scenario used July 21st, 2024 traffic, more than 6K flights in total covering French, Italian, Spanish, and Swiss airspace over a 24-hour period (06:00–17:00 UTC analysis window), with all flight plans assumed known at the start.

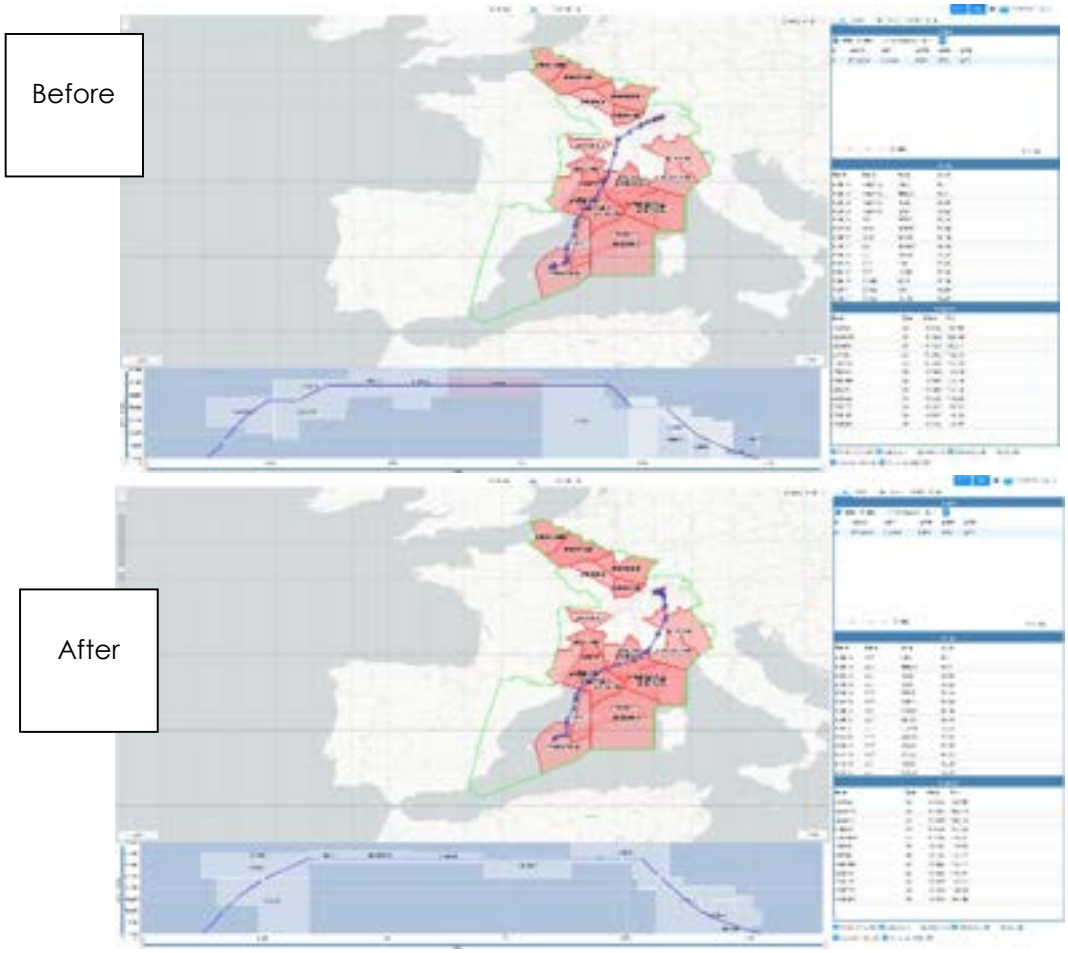


Figure 1. *Example of a flight rerouted by the solver. The airspaces that constitute the DCB problem are highlighted in red in the map. The boundaries of the ACCs of study are highlighted in green*

3. Results / Conclusions

Compared to the CASA baseline (111,086 total delay minutes; 48.5% of flights delayed), under the same conditions, a Lexiflow setup already achieved > 40% reduction in total delay. Further setups with dedicated rerouting enabled, for a limited percentage of flights, less than 5%, further reduces delay while confining all individual flight delays within lower caps. Several recommended configurations span a range of operating points: from aggressive delay minimization thanks to a higher amount of reroutings, to delay-only allocation setups (53,965 min). Network State Indicators suggest that optimized configurations can contribute to overall Network stability. Future work includes modelling airline behavioural responses to rerouting, combining CASA regulations with MCP assignments, and operational validation for higher Technology Readiness Levels.

Towards a more flexible ATCO Rostering – key elements, implementation roadmap and alignment with current regulations

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1. Introduction / Objectives

A modern and efficient Air Traffic Control (ATC) service provision is an essential pilar of aviation. Apart from ensuring a safe, orderly and fluent flow of air traffic, the Air Navigation Service Providers (ANSPs) are tasked with providing sufficient airspace capacity to guarantee the freedom of the air for airspace users, and to avoid delays or unnecessary detours. However, an increasing number of ANSPs suffer from a lack of ATC personnel, which increasingly forces them to collapse sectors, to regulate capacity, or to reduce operating hours in general **Error! Reference source not found.**. In addition, current practices, like the obligation to hold a unit endorsement, which can only be achieved with months of on-the-job training, further complicates this challenge **Error! Reference source not found.**. The objective of this research was therefore to find ways towards a more flexible ATCO rostering on one hand, and to define the roadmap for an operational implementation, aligned with current regulations, on the other hand.

2. Methodology

Methods are proposed that are able to partly compensate the mentioned lack of ATC personnel, which will persist at least for the next decade due to demographic reasons. Within this research, the key elements towards a more flexible ATCO rostering were defined, leading to a significant reduction of On-the-job Training time, as well as a reduction of endorsement maintenance effort. This allows ATCOs to get endorsed for more airspaces or aerodromes in parallel than today. The SESAR IFAV3 project therefore investigated ways and methods to increase the flexibility of ATCO rostering, together with a realistic roadmap for a relatively quick implementation into the operational air traffic management within 5-10 years. Within the project, several experiments were conducted to validate different strategies in the upper area control and remote tower control service provision, which are based on the mentioned key elements. This includes for example a set of Real-time simulations conducted by the German Aerospace Centre (DLR) and Eurocontrol at Maastricht Upper Area Control Centre, to validate the strategy of competency-based rostering **Error! Reference source not found.Error! Reference source not found.**. Another experiment was for example a series of workshops performed by DLR and Swedish ANSP LFV with ATCOs and operational experts to validate a flexible rostering strategy for Remote Tower Centres based on tool support and procedural adjustments **Error! Reference source not found.**. This paper will at first provide a review of key results, based on previous publications. On the other hand, the project defined concrete steps and practices how to implement IFAV key elements and strategies into the operational ATM in the different ATC environments, as guidance for the transition. In strong collaboration with the European Aviation Safety Agency (EASA) the project ensured that proposed methods and transition steps are in line with existing EU regulations and can therefore be introduced within the next years.

3. Results / Conclusions

This paper provides at first some background information about the IFAV3 project, and then elaborates the key elements towards a more flexible ATCO rostering in detail. It further briefly describes how these key elements were transferred into concrete strategies for upper area

control as well as for remote tower control service provision, which were then further tested in the various experiments. This is followed by a short review of key validation results. The main focus of the paper will be on the detailed description of the steps to implement the proposed means into the operational air traffic management, that were worked out together with EASA, and which ensure alignment with current European regulations. The paper closes with a short discussion and an outlook.

A Numerical Testbed for Analysing Air Traffic Controller Experience Complexity

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1. Introduction / Objectives

Recent research has introduced the Upper Airspace Skill-Level Index (UASLI) as a novel competency-based methodology for supporting flexible air traffic controller (ATCO) deployment beyond traditional endorsement structures. The UASLI combines competency monitoring and minimum competency level prediction within a common complexity assessment framework. Historical operational and training data quantify an ATCO's experience, whilst future traffic demand, sector characteristics, meteorology, and operational constraints are used to estimate competency requirements for upcoming operational scenarios within an Area Control Centre. By employing a set of measurable skill parameters, both processes enable a direct comparison between ATCO experience and future sector requirements.
Following initial development and validation activities, the next research challenge is the systematic assessment of the modelling assumptions underlying the UASLI. This work introduces a Monte Carlo simulation framework to investigate uncertainty dissemination, identify dominant input variables, and evaluate the influence of alternative temporal horizons on competency assessment outcomes.

2. Methodology

The proposed framework combines operational data analysis, probability distribution modelling, Monte Carlo simulation and sensitivity assessment, following fast-time simulation-based approaches for evaluating model assumptions for airspace complexity analysis**Error! Reference source not found.**.

Historical operational air traffic control data collected by Maastricht Upper Area Control over several months are used to characterise the variability of selected UASLI input parameters. For each parameter, empirical probability distributions are derived from the collected data, representing realistic variations observed during day-to-day operations. Figure 7 shows an example distribution for the aircraft heading at sector entry, illustrating how operational observations are transformed into probability distributions suitable for stochastic sampling.

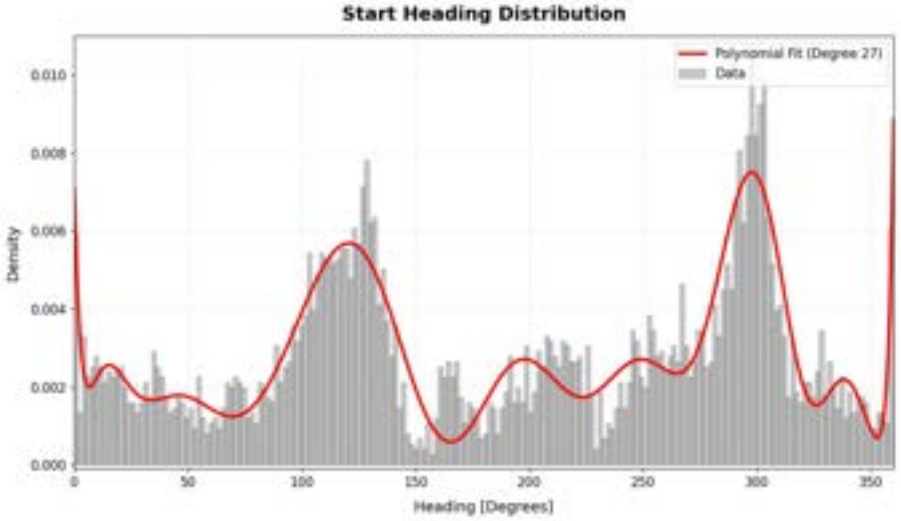


Figure 7. *Example empirical probability distribution derived from historical operational data. The distribution represents aircraft heading at sector entry (Start Heading) and is subsequently used to generate random input values for the Monte Carlo simulation.*

These probability distributions form the basis of the Monte Carlo simulation. Random variables are generated by sampling from the fitted distributions, enabling the creation of large numbers of synthetic but operationally realistic ATCO experience profiles and traffic scenarios. The initial investigation focuses on a subset of skill parameters representing different operational characteristics and mathematical formulations, including sector occupation, radio contacts and times, or aircraft types**Error! Reference source not found.**.
The framework evaluates two principal modelling assumptions. The first assumption concerns input sensitivity. Monte Carlo realisations are generated by sampling from the fitted input distributions. Resulting variations in skill parameter values are analysed to determine which operational inputs contribute most strongly to competency assessment outcomes and which parameters exhibit the greatest robustness against operational variability.
The second assumption concerns temporal horizons. In the monitoring context, the length of the retrospective observation period determines how much historical operational experience contributes to the competency assessment and remains an open modelling assumption. In the prediction context, competency requirements are assessed for a specific future operational scenario. However, the extent to which this scenario can be reliably predicted depends on the predictability of the underlying input parameters. Alternative monitoring periods and prediction lead times are therefore analysed to quantify their impact on competency assessment outcomes.
A targeted literature review of planning horizons in air traffic management is conducted to establish realistic temporal boundaries and associated uncertainty characteristics. Particular attention is given to the question of whether monitoring and prediction should be represented by identical or horizon-dependent probabilistic assumptions.

3. Results / Conclusions

The study is expected to provide the first systematic assessment of modelling assumptions within the UASLI methodology. The proposed framework will identify which operational inputs contribute most strongly to selected skill parameters and quantify the robustness of competency assessments under realistic operational variability.

Furthermore, the results are expected to provide evidence regarding the suitability of alternative temporal horizons and their influence on competency assessment outcomes. The framework is intended to support the next stage of UASLI development. By identifying modelling assumptions that have the greatest impact on resulting competency estimates and by providing a quantitative basis for future methodological refinements, the results ensure the transferability to other control centers.
More broadly, the work demonstrates how Monte Carlo simulation can support the development of competency assessment methodologies characterised by uncertainty, complex operational interactions and large volumes of empirical data.

Operational Validation of Flow-Centric Regulation Planning for Pre-tactical Air Traffic Flow and Capacity Management

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1. Introduction / Objectives

The primary objective of Air Traffic Flow and Capacity Management (ATFCM) is to ensure that forecasted traffic demand remains within the available capacity of both airports and airspace sectors, thereby minimizing congestion and optimizing operational efficiency. However, current ATFCM in Europe relies on sector-based regulations that are designed locally without coordination, which often propagate delays across the network and create secondary overloads elsewhere in unpredictable ways.
The SESAR DeepFlow project (Grant 101166935) develops a flow-centric operational framework that leverages machine learning to automatically extract major traffic flows, detect flow-level congestion architectures (flowspots and net-flowspots), and construct Demand and Capacity Balancing (DCB) Flows for more coordinated regulation. The methodology of this framework has been detailed in , where performance was benchmarked against the baseline optimisation algorithms. However, those studies did not assess how the resulting regulation plans compare with real operations. To address the gap, the objective of this study is to demonstrate that the flow-centric DeepFlow framework is operationally viable, by comparing the resulting performance against simulated sector-based operations in terms of operational KPIs defined by experts.

2. Methodology

The DeepFlow framework implements flow-centric operations for pre-tactical ATFCM, shifting from a localized, sector-based perspective to an integrated, network approach . Figure 1 illustrates how DeepFlow integrates into the cooperative functions of the Local Traffic Management (LTM) and Network Manager (NM).
Major flows are automatically extracted from planned trajectory data using unsupervised machine learning, replacing the manual process currently performed at the Network Manager Operations Centre (NMOC) at the strategic level. Along each major flow, *flowspots* are identified where one or more hotspots are crossed by the same flow, grouping high-complexity areas that collectively contribute to congestion. Where multiple major flows converge, the compounded components from their interaction are also captured as *net-flowspots*.
A hotspot dependency analysis then distinguishes network flowspots, which propagate

congestion across sectors and require coordinated NM intervention, from local flowspots, which can be resolved by the Local Traffic Manager within a single Area Control Centre (ACC). Within detected flowspots, Demand Capacity Balancing (DCB) flows, which are refined subsets of major flows sharing common DCB characteristics, are constructed as the primary units for applying coordinated DCB measures such as flow-level regulations. These candidates are evaluated by a First Planned First Served slot allocator that computes the resulting delay assignments and capacity overload relief. The regulations are planned sequentially so that the traffic demand remains current at each step, accounting for the demand-shifting effects that arise when multiple regulations interact.
The validation exercise covers two full-day pan-European traffic scenarios from the 2023 summer peak, 16 July and 29 July, using planned flight data from EUROCONTROL's DDR2. Three ACCs are focused on: Madrid, Bordeaux, and Paris, with hotspots identified by operational experts along the Southwest European axis. The result is compared with simulations in R-NEST, a EUROCONTROL model-based simulation tool for evaluating advanced ATM concepts, which applies the operational CASA algorithm to produce authoritative delay assignments. The performance is assessed across three tiers: regulation-level KPIs including period, rate, flights impacted, and delay distribution; ACC-level KPIs including delay metrics, peak overload, and hourly overload counts; and flight-level KPIs including route length, duration, and fuel consumption.

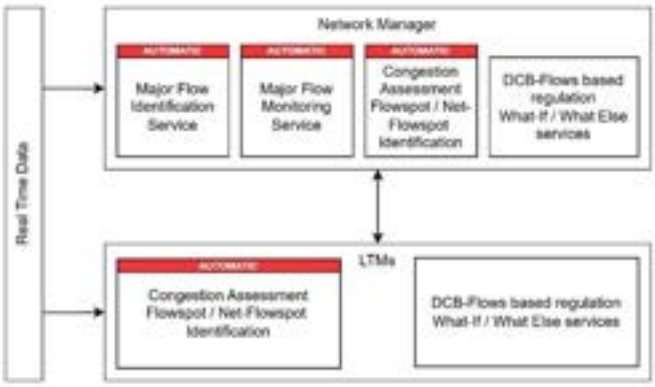


Figure 1. *Network Manager LTM interaction*

3. Results / Conclusions

R-NEST simulations show that the current sector-based approach required 159 regulations on 16 July and 166 on 29 July across Madrid, Bordeaux, and Paris ACCs, generating total ATFM delays of approximately 166,000 and 270,000 minutes respectively. Bordeaux ACC absorbed the largest share, with delay per flight reaching 37 min/flight on 16 July and 62 min/flight on 29 July. By contrast, the flow-centric regulation plans produced by the DeepFlow framework achieved significant overload relief with much fewer regulations and a more selective flight impact, delaying only 1 to 5% of total flights. The multi-level KPI comparison demonstrates that flow-centric approach produces operationally reliable solutions by concentrating measures on the flows, reducing both the congestion and delay on heavily loaded ACCs. These results provide evidence that a transition from sector-based to flow-centric operation is both feasible and beneficial for European ATFCM operations.

Validation of HYCON Multi-Link Architecture for Resilient Surveillance

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1. Introduction / Objectives

The rapid growth of global air traffic, driven by post-pandemic recovery and the integration of Unmanned Aircraft Systems (UAS) and Advanced Air Mobility (AAM), is placing critical pressure on the 1090 MHz spectrum supporting ADS-B. In high-density environments, increasing message collisions and signal garbling threaten surveillance integrity and scalability **Error! Reference source not found.**. This study addresses this bottleneck by introducing Alternative Surveillance (A-SUR) **Error! Reference source not found.**, a resilient architecture that augments Air Traffic Control (ATC) through a Hybrid Communications Network (HYCON) **Error! Reference source not found.**. A-SUR dynamically distributes aircraft 4D position data across heterogeneous safety and non-safety links, including LDACS, VDLm2, SATCOM, and LTE/5G networks, as illustrated in Figure 1. State-of-the-art of multilink avionics research focuses on improving communication resilience and coverage through heterogeneous datalinks **Error! Reference source not found.**, whereas this work specifically evaluates whether such an architecture can maintain surveillance continuity and integrity while relieving congestion on the overloaded 1090 MHz channel. The key innovation lies in enabling scalable, globally continuous surveillance via software-driven, multi-link data dissemination, while remaining complementary to independent ground systems for integrity monitoring.

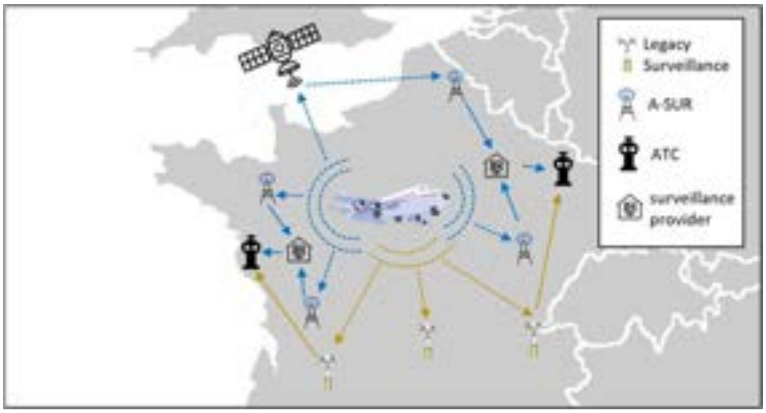


Figure 1. Aircraft-based A-SUR concept.

2. Methodology

The study employs a simulation-based methodology to evaluate the performance of A-SUR in reducing spectrum congestion and improving surveillance robustness. Aircraft 4D position information is transmitted over the HYCON network, combining multiple safety (e.g., LDACS, VDLm2, SATCOM) and non-safety (e.g., 5G) datalinks with diverse performance characteristics.

A high-density airspace scenario is modelled to emulate interference conditions where ADS-B performance degrades due to message collisions and signal garbling. Within this environment, surveillance data is distributed across multiple links, enabling comparative

assessment of latency, reliability, and continuity. The heterogeneity of communication technologies is explicitly considered to evaluate their ability to meet surveillance performance requirements.
On the ground, a centralized processing system ingests and fuses data from both ADS-B and A-SUR sources. The fusion algorithm accounts for link-dependent degradations, including transmission delays and position uncertainty, to assess robustness against asynchronous and uneven data inputs.
Two validation streams are conducted: the first analyses communication and surveillance performance under nominal and degraded conditions, while the second evaluates fusion accuracy and track stability, targeting high positional accuracy and reduced track inconsistencies relative to single-source surveillance.

3. Results / Conclusions

The results demonstrate that the proposed A-SUR framework significantly enhances surveillance performance compared to ADS-B alone, particularly in high-density and interference-prone environments. Multi-link operations consistently maintain high integrity and continuity, with LDACS and 5G achieving over 99.9% of service performance (against up to 78% with ADS-B) and meeting stringent performance requirements even under increased traffic loads or in the absence of ADS-B coverage. In contrast, ADS-B exhibits severe degradation under congestion, highlighting its scalability limitations.
The data fusion process successfully combines heterogeneous inputs while preserving positional accuracy, maintaining errors below 50 m in the vast majority of cases. Although some sensitivity to packet loss and uneven data quality is observed, these limitations are manageable through algorithm refinement rather than architectural changes. Overall, the findings confirm that a multi-link, avionics-driven surveillance approach can ensure scalable, resilient, and globally continuous surveillance, with strong potential to support future high-density airspace operations.

Multistatic Passive Radar for ATM Surveillance: a simulation study in relevant environments

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1. Introduction / Objectives

The modernization of the Air Traffic Management (ATM) needs to accommodate traffic growth and increase the
resilience and interoperability of the Communication, Navigation, and Surveillance (CNS) infrastructure in Europe. While conventional primary radars face decommissioning due to high costs, secondary surveillance systems such as Automatic Dependent Surveillance-Broadcast (ADS-B) are increasingly vulnerable to spectrum congestion and Global Navigation Satellite System (GNSS) interference. This work further advances the research addressing the LDACS-SUR approach, a multistatic passive radar system that leverages the forthcoming L-band Digital Aeronautical Communication System (LDACS) signals as signals of opportunity for aircraft surveillance , as depicted in Figure 1.



Figure 1: LDACS-SUR passive multistatic radar.concept

Having previously defined a network distribution in , in this work we evaluate the performance of this approach in relevant environments according to the performance requirements defined in the ESASSP . With these numerical studies, the first insights are gathered into the operational feasibility of the technology.

2. Methodology

The study is conducted in two Italian scenarios: Milan TMA (Terminal Maneuvering Area) and Perugia CTR (Control Zone). As a first assessment, a real trajectory is chosen for each scenario, and the performance is evaluated across the entire selected flight path within the airspace. A performance study is performed using a target detection and tracking performance analysis tool developed in the context of the SESAR ASTONISH Project. The simulation tool integrates scenario orography data, network topology, and signal characteristics. The reference and surveillance signals are synthesized by calculating time-variant power levels for the direct path and target echoes for each node across all Tx-Rx pairs. Next, the platform computes the baseline distance, the dynamic bistatic range, and the velocity based on the target's flight path and the system's geometry. These parameters

are subsequently modulated onto the signal through a signal generation module that produces high-fidelity synthetic waveforms for performance analysis. To evaluate the suitability of the proposed LDACS-SUR approach in the ATM context, it is essential to measure its performance against established benchmarks. Consequently, this study adopts the performance requirements defined in the Eurocontrol Specification for ATM Surveillance System Performance (ESASSP) as the primary framework for comparison. This document provides a set of performance requirements for various surveillance technologies to ensure they meet the minimum performance levels necessary for air traffic services. By utilizing these performance requirements, an analysis of the performance of the proposed concept is derived. Given the scenarios under study, we specifically employ the requirements specified for the 3 NM minimum aircraft horizontal separation. This approach presents the first step towards validating the operational feasibility of LDACS-SUR for ATM surveillance.

3. Results / Conclusions

The performance results of LDACS-SUR in the environments of interest are summarized in Table 1.

Table 1: Performance results of LDACS-SUR.

Description	Required value (mandatory/recommended)	Perugia CTR	Milano TMA
Measurement interval	5 / 4 s	4 s	4 s
Probability of update (horizontal)	97 / 99 %	100 %	99.7%

Ratio missed 3D (long gaps)	0.5 % / -	0.0 %	0.0 %
Horizontal position RMS error	300 / 230 m	229.9 m	248.8 m
Ratio correlated horizontal errors	- / 0.03%	0.0 %	0.6%
Rate of climb/descent RMS	250 feet/min stable, 500 feet/min climb, descent / -	1879.0 feet/min	1367.9feet/min
Track velocity speed RMS	Less than or equal to 4 m/s for straight line, less than or equal to 8 m/s for turn / -	3.0 m/s	1.9m/s
Track velocity angle RMS	10° straight, 25° turn / -	1.0°	1.5°

As a conclusion, LDACS-SUR generally meets the surveillance performance requirements in accordance with the specification for the conducted study.

Acknowledgements: This research is carried out in the framework of the SESAR ASTONISH project, supported by the SESAR 3 Joint Undertaking and its members under grant agreement No 101167383 under European Union's Horizon Europe research and innovation programme. Funded by the European Union. Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or SESAR JU. Neither the European Union nor the granting authority can be held responsible for them.

AIrfield: Regulation-Aware AI-Assisted FOD Reporting in Airport Operations — A Zagreb Airport Case Study

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1. Introduction / Objectives

Foreign Object Debris (FOD) management is a safety-critical airport operation governed by EASA Regulation (EU) No 139/2014 and FAA AC 150/5210-24, which mandate systematic procedures for FOD prevention, detection, removal, and reporting, alongside structured data collection for safety analysis. Despite these requirements, current reporting practices remain predominantly manual or semi-manual, especially in smaller airports or resource-constrained operational environments where the deployment of automated detection technologies and integrated digital reporting systems is limited. Such operator-dependent practices can lead to inconsistent records, limited traceability, and reduced analytical value for Safety Management Systems.

This work, developed within the Horizon Europe SEISMEC project , proposes a regulation-aware digital framework that reconceptualises FOD reporting as an assisted, structured, and compliance-driven workflow rather than a passive data-entry task. The framework combines a structured mobile application with a Multimodal Large Language Model (MLLM)-based procedural companion that embeds regulatory and operational knowledge. A human-centric evaluation layer incorporating physiological and egocentric sensing further assesses operator interaction and cognitive load in real-world conditions at Zagreb Airport.

2. Methodology

The framework builds on the FOD Control Programme implemented under ADR.OPS.B.016 within the airport's Safety Management System. It integrates three interdependent components: a structured mobile application, a geospatial and operational context model, and an MLLM-based procedural companion.

The mobile application provides a reporting interface aligned with operational workflows, supporting both inspection and cleaning activities. It incorporates predefined airport zones, standardised input fields for FOD categorisation, mandatory image capture, and optional GPS-based localisation, ensuring structural consistency between field observations and regulatory reporting schemas.

The geospatial layer encodes domain knowledge on FOD sources and risk-stratified zones, including aircraft stands, taxiways, runways, maintenance areas, and cargo zones, together with typical FOD origins such as aircraft handling, ground support equipment, construction activities, and environmental factors. This contextual model both guides and constrains the reporting process, reducing reliance on operator judgement for zone attribution and source identification.

At the core of the framework, the MLLM companion integrates multimodal inputs, including inspection images, GPS location, zone context, and optional operator annotations, and reasons over them using procedural knowledge extracted from regulatory guidelines and operational practice . The companion supports the operator by proposing consistent FOD

categorisations, flagging incomplete fields, and resolving reporting ambiguities such as partial zone coverage or conflicting annotations. This builds on prior work in evidence-grounded annotation for safety-critical inspection and image-text pairing for runway defect detection .
A central claim of the framework is that AI-assisted reporting reduces the cognitive burden of FOD inspection without compromising reporting quality. To validate this empirically, conventional survey-based assessment is insufficient in dynamic airside environments where operators cannot interrupt task execution to self-report. Instead, wearable physiological sensing and egocentric video capture are deployed during live inspection tasks at Zagreb Airport to provide continuous measurement of cognitive load, attentional allocation, and interaction efficiency. These signals serve as objective ground truth for evaluating whether the MLLM companion genuinely supports the operator's reporting workflow under real operational conditions, rather than adding cognitive overhead.

3. Results / Conclusions

The framework is evaluated in the operational environment of Zagreb Airport, demonstrating applicability across real-world FOD inspection and reporting workflows. Results indicate meaningful gains in reporting completeness and consistency, particularly in complex cases involving ambiguous zone attribution and heterogeneous FOD observations. The structured interface combined with MLLM assistance reduces inter-operator variability while preserving the operational flexibility required in dynamic airside environments.
Integration of geospatial and procedural knowledge strengthens traceability and supports downstream analysis of FOD sources and recurrence patterns, directly addressing regulatory expectations for evidence-based Safety Management. The human-centric evaluation layer further reveals how AI assistance modulates cognitive load and operator attention, offering empirical insights into human–AI interaction quality beyond standard usability metrics.
Collectively, these results demonstrate that regulation-aware, human-centric AI systems can move airport FOD management beyond detection, achieving operationally integrated, compliant, and analytically tractable reporting, with transferability potential across other safety-critical aviation domains.

Meteorological Operating Limitations for a Regional Air Mobility Network

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1. Introduction / Objectives

Electrified CS-23 aircraft are approaching market readiness and offer substantial potential for integrating Regional Air Mobility (RAM) into the transport system. For a representative small airfield located near Aachen, Germany, demand-based network analyses indicate promising connections using small aerodromes. However, scheduled commercial operations within such a network require reliable access to airports that are often limited to visual flight rules (VFR). Effective operability therefore depends strongly on meteorological conditions, particularly cloud ceiling and visibility. Historical METAR-based assessments at German aerodromes indicate that VFR conditions are unavailable for approximately 16 % of observed periods ; at network and route level, the resulting operational limitations are expected to be considerably greater. While conventional precision-approach infrastructure such as ILS

(Instrument Landing System) is generally uneconomic for small aerodromes, satellite-based approaches such as LPV (Localizer Performance with Vertical Guidance) may provide comparable minima to ILS CAT I with substantially lower local infrastructure requirements. This study quantifies the additional network operability enabled by LPV for an RAM network centred on a representative small airfield near Aachen.

2. Methodology

The analysis builds on a demand-feasible RAM network centred on a representative small airfield near Aachen. The initial network comprises connections to German and international NUTS 3 regions that offer relevant travel-time savings compared with forecasted road and rail transport in 2040. Routes are retained if they fall within the assumed aircraft range, satisfy defined minimum demand thresholds in terms of weekly flight frequency, and can be served considering key infrastructure constraints, particularly runway length.



Figure 1. *Integration of a representative small airfield near Aachen into an eCTOL transport network:19-seat aircraft, 400 km range; red: minimum flight frequency of 5 flights/week; yellow: 2 flights/week; green: 1 flight/week.*



Figure 2. *Intra-North Rhine-Westphalia eCTOL transport network: 9-seat aircraft, 400 km range, minimum of 1 flight/week per route. (Source: DLR)*

In a second step, the demand-feasible network is extended to an operations-feasible network by incorporating meteorological and approach-procedure constraints. Historical aerodrome weather conditions are evaluated using METAR observations for representative summer and winter periods. For each network node, data from the nearest suitable reporting station are assigned. The assessment focuses on visibility and cloud ceiling as operationally relevant parameters for departure and arrival accessibility. Two operating scenarios are compared. The first represents VFR-based operation under regulatory requirements with particular emphasis on visibility and cloud ceiling at both origin and destination. The second scenario constitutes a sensitivity analysis in which selected small aerodromes are assumed to be equipped with LPV-capable approach procedures. The objective is to evaluate whether cost-effective satellite-based vertical guidance, as an alternative to conventional ILS infrastructure, could substantially improve the operational feasibility of the considered flight network. In particular, the analysis assesses how the less restrictive operating minima associated with LPV approaches compared with VFR operations affect aerodrome accessibility under adverse weather conditions and quantifies the resulting percentage improvement in operational performance. For each scenario and season, aerodrome accessibility is determined for every observation period and aggregated at route level, requiring simultaneous accessibility of both the departure and destination aerodromes. Based on the assumption that an IFR pickup can be obtained once the aircraft reaches the

required altitude after departure, the assessment is limited to the weather conditions at the departure and destination aerodromes; en-route weather conditions are not considered. Accessibility is evaluated against the operating minima applicable to the respective procedure scenario. The resulting route-level availability quantifies the share of services that can be operated under each scenario.

3. Results / Conclusions

The results quantify the extent to which weather-related accessibility affects the operational feasibility of the considered RAM network. Under VFR-based operation, the requirement for simultaneous accessibility of both departure and destination aerodromes limits route-level availability, particularly during periods of reduced visibility and low cloud ceilings. The LPV sensitivity scenario examines the potential network-level benefit of equipping selected small aerodromes with satellite-based approach procedures featuring less restrictive operating minima than VFR operations. The analysis is intended to determine the resulting percentage improvement in operable services rather than to demonstrate the technical or economic implementation feasibility of LPV at individual aerodromes. The findings will indicate whether targeted enhancements of approach capability at strategically relevant network nodes can substantially improve the reliability and operational robustness of scheduled regional air services.

Advanced conflict resolution algorithms and operational scenarios in ASAS simulator

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1. Introduction / Objectives

In this paper we focus on the conceptual design and demonstration tools for an aviation congestion mitigation strategy and complex operations, pairing ATFM - Air Traffic Flow Management with demand management to safely align airspace operations with airport infrastructure capacity. Eventually, by combining tactical re-routing, schedule controls, and advanced digital integration, our concept minimize costly delays, global emissions, and fuel burn.

ASAS was designed and implemented as a hybrid distributed platform with HIL – Human-in-the-loop capability to be utilized in both aviation and non-aviation context (such as military and board wargaming to model tactical, operational, and strategic warfare) . This system has already been demonstrated in relation with INCAS SESAR activities, in particular SPATIO Solution 1A . Integration with distributed real time data information centers, mainly for real-time traffic data (both for RADAR and ADS-B) and weather conditions via dedicated tools is a key component in this system. Our collision avoidance models and AI driven prediction algorithms are implemented so that we can anticipate the ATC challenges and provide solution for unsegregated airspace operations.

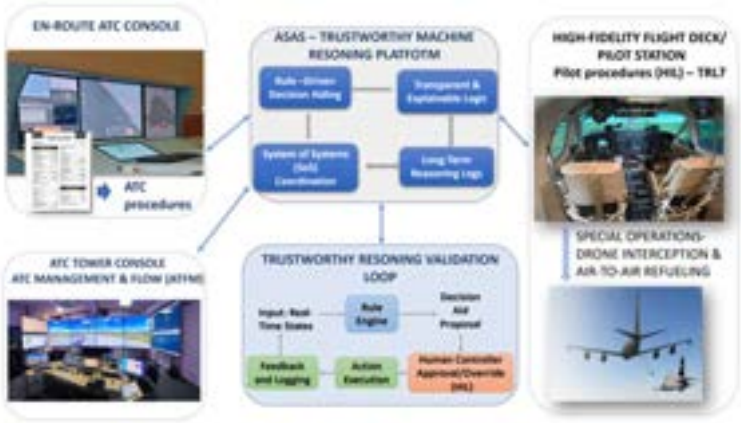


Figure 1. *ASAS Simulator – Basic integration*

2. Methodology

Here we introduce the framework for ATM simulation systems to operate continuously across two distinct layers of conflict management, to keep aircraft separated by standard safety margins. We define a first phase as SF-Strategic Phase, initiated prior to departure, where we aim for conflict-free 4-Dimensional trajectories to route aircraft around high-density zones, severe weather, or restricted conflict areas. In this SF simulations we absorb traffic demand in advance to ensure the airspace remains stable. Our second layer is the TP - Tactical Phase, with dynamic aircraft management while in flight, when sudden changes like pop-up traffic or adverse wind conditions may be the cause for a traffic deviation. We introduce in both phases new collision avoidance models (xCAS) and use real-time radar sensing and sensor data to calculate new avoidance vectors for ATCOs -air traffic controllers.
Our ASAS simulator (Fig. 1 integrates both professional software tools (e.g. Lockheed Martin Prepar3D v5 with SDK v5 SimConnect) and additional Open-Source Platforms for flight planning, navigation and moving map tools, designed for flight simulation (e.g. LittleNavMap). ASAS utilize thousands of objects and variables (including environmental factors and dynamic air traffic) to model multi-domain evolutions, build flight plans, view detailed operational environment, both in on-ground/airports and enroute/TMA operations, with realistic chasing cameras and local synthetic views and track aircrafts in real-time. The core platform functions as a low-latency backbone that interfaces a diverse cluster of high-fidelity HIL simulators, distributed flight engines (aircrafts and drones included), and live operational inputs (pilots and ATC). The network hardware node configuration includes a complete Virtual Air Traffic Control (ATC) Tower, a certified ATC Approach console, a set of full-scale Level-D aircraft cockpits(A320 Neo, B737 NG, IAR-99 TD) 6-DOF type-rated Beechcraft C90 GTx research simulator. To mimic operational airspace density, the environment actively ingests real-world traffic data streams (from collective ADS-D resources world-wide and RADAR) alongside synthetic background traffic.

Specific new tools are introduced via SimConnect capability in P3D simulator engine. This takes into account our algorithms for trajectory prediction, local traffic conditions and T-CAS/A-CAS new concepts. Globally, our tools assist the ATC to perform efficient missions in unsegregated airspace(Fig. 2), under fully compliant safety procedures.



Figure 2. *Air refueling in air policing mission*

3. Results / Conclusions

Globally, we present results for ASAS simulator operating at a high technology readiness level (TRL 7), offering a fully connected, legally and procedurally compliant synthetic airspace ATM environment. Some selected scenarios (Fig. 2 – air refueling in air policing mission) clearly demonstrate how, by bridging real-time machine-reasoning capabilities with physical simulator clusters, this environment provides a scalable infrastructure for developing and stress-testing advanced controller decision-support systems during non-segregated special flight operations, ensuring total safety of operations without disrupting standard civil traffic flows. The developed TRL 7 infrastructure and our AI-driven algorithms provide a robust, validated, and high-fidelity environment for ATM research and advanced operations. It also establishes a powerful benchmark for evaluating next-generation civil-military coordination tools, multi-agent operations, and advanced machine-reasoning decision support within non-segregated operational airspaces.

Simulation-Based Assessment of TBO and xCAS Concepts

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1. Introduction / Objectives

The increasing demand for air transportation, combined with the growing complexity of airspace operations requires more efficient and predictable ATM solutions. Trajectory-Based Operations (TBO) are considered a key component of future ATM systems, enabling improved trajectory predictability, enhanced airspace utilization and more efficient traffic flow management through the sharing and continuous updating of 4D trajectory information . However, implementing TBO remains challenging due to differing operational requirements, dynamic airspace restrictions and the need for effective stakeholder coordination. Moreover, airport surface operations at congested hubs remains a critical challenge for safety and efficiency . The eXtended Conflict Awareness System (xCAS) is an aircraft-centric platform that has been demonstrated for real-time ground conflict detection within the ASAS hybrid distributed simulator at TRL7. The challenge is to evolve xCAS from reactive conflict awareness toward proactive, data-driven conflict resolution, extending the validated detection foundation rather than replacing it.
This study proposes a simulation-based framework for assessing TBO and xCAS in a

representative unsegregated airspace environment. The objectives of the work are to develop and validate discrete-event simulation models in supporting more efficient coordinated airspace management.

2. Methodology

A simulation-based methodology was developed to assess the impact of TBO on operational performance and trajectory adherence in unsegregated airspace environment. We use a discrete-event simulation model implemented in Arena Simulation Software to represent airport and terminal area operations, focusing on the interaction between aircraft arrivals, departures, and runway resource allocation processes. Aircraft entities are generated according to predefined traffic demand patterns combined with stochastic variations to reproduce realistic operational conditions. Each aircraft is assigned a set of operational attributes, including traffic category, operational priority and planned trajectory parameters. A dynamic trajectory-based sequencing mechanism is implemented through a priority scoring process, allowing aircraft to be sequenced according to operational needs and trajectory-related information rather than solely by order of arrival. The model may also incorporate dynamic airspace constraints associated with military activities (Fig. 1). These constraints are introduced through temporary activation and release of military operational areas, resulting in varying levels of available operational capacity. This approach reflects the principles of Flexible Use of Airspace (FUA) and enables the assessment of TBO performance under changing airspace availability conditions.

xCAS predictive conflict detection modules were implemented within the INCAS ASAS simulator environment (Fig.2) using the Prepar3D SimConnect SDK, with emphasis on airport surface surveillance and conflict anticipation during taxi, pushback, takeoff, and landing operations. The proposed approach focuses on a high-resolution ground monitoring area covering a 400-meter proximity zone around the aircraft. The core algorithmic contribution consists of a real-time predictive engine deriving aircraft motion vectors from temporal position samples provided by the Prepar3D SimConnect, rather than relying exclusively on reported heading and ground speed values. Using relative position and relative velocity vectors, the system computes the Closest Point of Approach (CPA) and Time to Closest Point of Approach (TCPA) for each tracked aircraft. TCPA is obtained through minimization of the relative distance function over time, while CPA is evaluated by forward trajectory projection at the computed convergence instant.



Figure 1. *Integrated Simulation Framework for TBO*



Figure 2. *Potential congestion areas – LROP case*

Conflict assessment operates on predicted future state rather than instantaneous geometric separation. Three structured awareness levels are defined at 300 m, 150 m, and 50 m, enabling early-stage identification of converging traffic situations before critical proximity thresholds are reached. The proposed methodology provides actionable warning intervals of approximately 30–60 seconds in representative airport surface scenarios, improving pilot situational awareness in congested operational environments.
Several operational scenarios are considered. For TBO, the baseline scenario represents conventional ATM operations based on first-come, first-served sequencing and tactical traffic management. Advanced scenarios introduce trajectory-based sequencing principles associated with dynamic civil-military airspace constraints, allowing the evaluation of trajectory management capabilities under increased operational complexity.

3. Results / Conclusions

The performance assessment is based on a set of operational and trajectory-related Key Performance Indicators (KPIs), including average delay, runway throughput, queue length, runway utilization and trajectory adherence. Trajectory adherence is evaluated by comparing planned and actual operational times, providing a measure of the system's ability to maintain aircraft operations close to their intended trajectories. Multiple simulation runs are performed under different traffic demand levels to ensure statistical consistency and evaluate the robustness of the proposed approach. Preliminary assessment demonstrates the capability of the proposed ASAS simulation framework to represent TBO and also include xCAS in unsegregated airspace environment and to evaluate their impact on operational performance. Our approach provides a flexible environment for investigating the benefits of TBO concepts and xCAS performance. Future work will focus on more complex scenario analysis and quantitative assessment of operational improvements under varying traffic conditions.

Air risk assessment for long-range UAS operations under U-space

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1. Introduction / Objectives

While UAS operations are currently restricted to segregated environments, the European regulation introduced the U-space framework with the aim to facilitate the development of long-range operations on a routine basis. This framework encompasses the certification of a U-space service provider, the designation of a U-space airspace, the adherence to operational requirements and, for manned aircraft wishing to enter the U-space airspace, the mandatory equipage with an electronic conspicuity device.
The context of this paper is an industrial project aiming to develop U-space corridors for the delivery of medical goods. The paper describes the approach taken and the mitigation means proposed to address the air risk, i.e. the risk of mid-air collisions between the unmanned and manned aircraft. It combines the model-based safety analysis of the U-space services working along with a detect-and-avoid system, and the qualification of the UAS detect-and-avoid system through fast time and real time simulations.

2. Methodology

The management of air risk during long-range operations under U-space requires several tasks to be performed during the preparation and the execution phases of the mission. A preliminary step is the certification of the U-space service provider (USSP) which includes at least the provision of four mandatory services: network identification, geo-awareness, flight authorization and traffic information – these two last services contribute to the strategic and tactical mitigations of the air risk.

The next task it to define a concept of operations, including the operational volumes, which in the case of medical goods delivery take the form of corridors between, for instance, a large hospital and a medical laboratory. The length of these corridors is typically of several kilometers, so that the drone is beyond visual line of sight of the remote pilot throughout most of the flight duration. The design of their exact geography results from different constraints, with the need to reduce the possible risks and to insure the quality of the communication link between the drone and its ground station, as well as a complete coverage of the flight volume by the traffic surveillance antennas deployed by the USSP. Within our project, an optimization tool allows to fasten this time-consuming process.

Once the corridors are defined, a preliminary airspace risk assessment (ARA) is established and submitted to the competent authority. The process follows the Eurocontrol guidelines for the preparation phase, including the description of the operational environment and the identification of the main risks. Regarding air safety, an initial risk analysis is then performed using the SORA methodology. The proposed corridors are mostly located over sparsely populated areas, in uncontrolled airspace and limited in height to 400 feet above the ground level, so that the initial air risk class can be considered as low (ARC-b). In addition, the U-space traffic information service supports the situation awareness of the pilot and thus constitutes a first level of mitigation. Nevertheless, under the terms of SORA a detect-and-avoid (DAA) system with low performances is required to guarantee an acceptable level of safety towards manned aircraft that may enter the operational volume. Based on previous work, we then focus on the safety analysis of the combination of the U-space services with the DAA system, using a model-based approach (Figure 8).



Figure 8. *An example sequence diagram of separation management modeled in the safety analysis.*

The airspace assessment includes the identification of the legacy traffic in the operational volume. A strong hypothesis is that this traffic shall be equipped with electronic conspicuity (EC) equipment - in compliance with the EU regulation. The proposed DAA system uses the EC signals to insure both separation and collision avoidance. A simulation tool (Figure 9) is used in real time with remote pilots in the loop to qualify the usability of the system (HMI

design, alerting timelines, guidance information) and in fast time trials to quantify its performance criteria (risk ratios, sensitivity to detection uncertainties and encounter parameters).

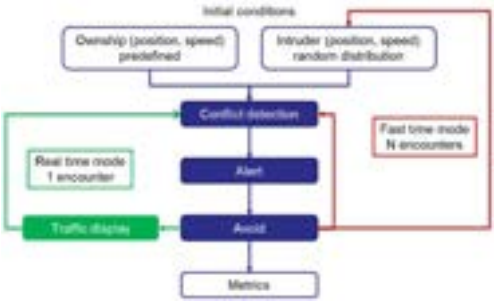


Figure 9. *Flowchart of the simulation logic with real time and fast time modes.*

3. Results / Conclusions

This paper reviews the different aspects and steps involved in the preparation of long-range operations under U-space. These operations take place in a designated U-space airspace where a DAA system supplements the U-space services to mitigate the air risk. The model-based safety analysis provides an exhaustive understanding of the combinations of possible technical or procedural failures, which may hinder safety. The paper details this analysis, as well as the simulation tools developed for the qualification of a proposed DAA solution. These tools objectively support the safety argumentation required for operational approbation. We also tested hypotheses on specific issues that are not yet frozen in the regulation or existing standards, regarding the airspace risk assessment, the responsibilities of the actors and the DAA design parameters.

Funding: This research was funded in part by the French government as part of the France 2030 initiative.

Real-Time Distributed Client–Server Simulation for Trajectory Management of UAS in a Structured Urban Airspace Network

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1. Introduction / Objectives

The safe integration of Unmanned Aircraft Systems (UAS) into low-altitude urban airspace is a central objective of the European U-space framework, which defines digitally provided services for traffic information, flight authorization and conflict management. While many platforms already cover pre-flight services, validated tools for autonomous in-flight management remain comparatively scarce, and ongoing European efforts such as the SESAR 3 JU ENSURE project are still maturing the U-space–ATM interface. This work develops and tests, in a fully virtual environment, a distributed client–server simulation system for real-time urban UAS traffic management. The objective is a low-cost software testbed, designed to be consistent with U-space in-flight services, that couples a six-degree-of-freedom (6DOF)

vehicle model with density-aware trajectory routing over a network architecture mirroring the federated structure of a real deployment.

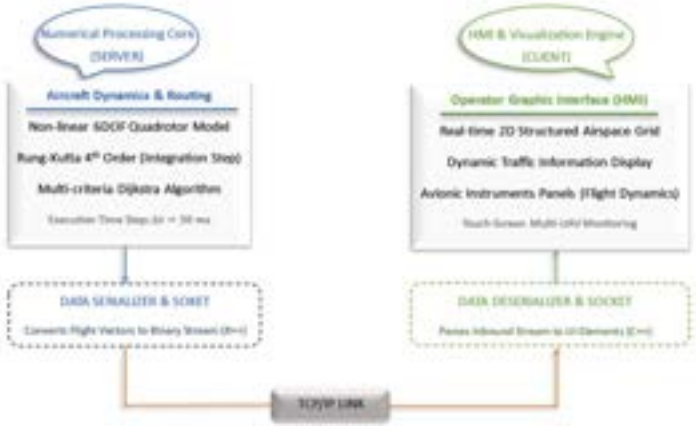


Figure 1. *Architecture of the distributed client–server air-traffic monitoring system.*

2. Methodology

The framework separates computation (SERVER) from visualization (CLIENT), communicating over a TCP/IP socket interface. The urban airspace is modelled as a logical network of nodes and bidirectional corridors covering an 8 × 8 km area, with segment lengths of 1 km, 2 km and 1.41 km and a dedicated emergency corridor for each direction; each node represents a relevant urban location such as a launch or landing point. On the SERVER, an optimal route between a selected origin and destination is computed with a Dijkstra shortest-path algorithm extended by a multi-criteria cost function that weights distance, per-segment traffic density and vehicle priority, so that congested corridors are avoided. This graph-based, congestion-aware routing is consistent with approaches reported for structured urban airspace . The planned route is then flown by a 6DOF nonlinear quadrotor model that propagates position, velocity, attitude and angular rates at each step, in line with established quadrotor trajectory-tracking formulations . A compact 54-byte state packet is transmitted to the CLIENT, a C++ graphical interface that renders the network, vehicle icons and live trajectories and lets the operator inspect per-vehicle parameters such as speed, distance and estimated arrival time. Test scenarios use different origin–destination pairs, generated automatically rather than predefined, and are assessed through communication stability, packet integrity, deviation from the optimal route and trajectory behavior.

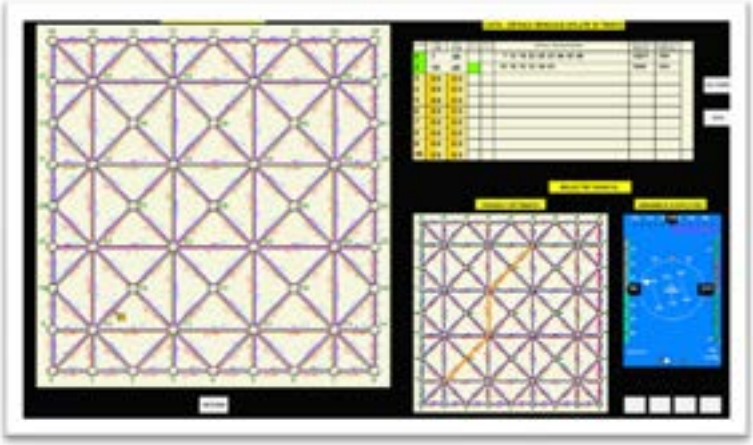


Figure 1. *Logical urban air-traffic network (8 × 8 km) of nodes and bidirectional corridors used for routing.*

3. Results / Conclusions

Across the tested scenarios the system maintained stable, real-time data exchange between the computation and visualization modules, without packet loss or perceptible display delay, and the automatically generated routes showed minimal deviations from the optimal path while avoiding congested corridors. The 6DOF trajectories remained consistent with the planned routes, and the synchronized display correctly reflected vehicle state throughout each run. These qualitative results indicate that the distributed client–server design is a viable, low-cost testbed supporting U-space in-flight services and a sound basis for adding collision-avoidance and ATM-coordination functions.

Acknowledgement: This work was carried out within the Nucleu Programme research project PN 23 17 06 03, "Advanced concepts for Advanced Air Mobility (AAM) and Unmanned Aircraft Systems (UAS) Traffic Management (UTM)", funded by the Romanian Ministry of Research, Innovation and Digitalization under the AEROEXPERT 2023–2026 programme.

Automatic Unmanned VCA Operations in Mixed Airspace Environment: the Case of OPERA Project

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1. Introduction / Objectives

Key limitations affecting the current Unmanned Aircraft System (UAS) operations include the long and complex processes required for obtaining operational approval, and operational flexibility due to constraints in airspace access . The presented solution explored these limitations and proposed a streamlined operational approval process, enhanced integration of U-space services and digital infrastructure, resulting in improved coordination between U-space Service Providers (USSP) and Air Navigation Service Providers (ANSP), adaptation of existing Air Traffic Control procedures, and the incorporation of advanced automation

functions onboard the VTOL Capable Aircraft (VCA) and in the ground control station.
The solution validated automatic VCA operations, covering:

- UAS operator's (UASO) combined flight intent expressed in Flight Authorisation Request (FAR) and Flight Plan (FPL), and processed by both USSP and ANSP;
- Procedures for Remote Pilots (RP), Air Traffic Control Officers (ATCO) and Flight Information Service Officers (FISO) to manage transitions of automatic VCA across different categories of airspace;
- Detection of Command and Control (C2) link loss and mitigation procedures.

The implementation focuses on streamlining these processes from both stakeholders and operating environment perspectives through development of a compatible set of operational (procedures, requirements, services) and technical enablers.

2. Methodology

The solution concept defined and developed for unmanned eVTOL (automatic VCA) operations:

- Processes for transferring operational flight intent information between FAR and FPL;
- Procedures for RP, ATCO and FISO needed for transition between different categories of airspace;
- Procedures for managing loss of the C2 link.

The validation approach was based on the assessment of the abovementioned concept elements through a series of expert level discussions focused on the detailed use cases and identifying the operational differences . The supporting technology and system elements - particularly the interoperability between air and ground system elements - were validated through two demonstration activities.
The concept was validated within four exercises which defined and detailed the operational processes, tested them in dry runs and simulations, demonstrated the developed key services and solution technology functionalities. The final RTS with virtual NUUVA V300 aircraft and human actors in the loop - operational staff: ATCO, RP, and (A)FISO validated the overall concept.

3. Results / Conclusions

The project solution produced number of new enablers to be included in ATM architecture (Figure 1) which enables the concept implementation for automatic VCA.

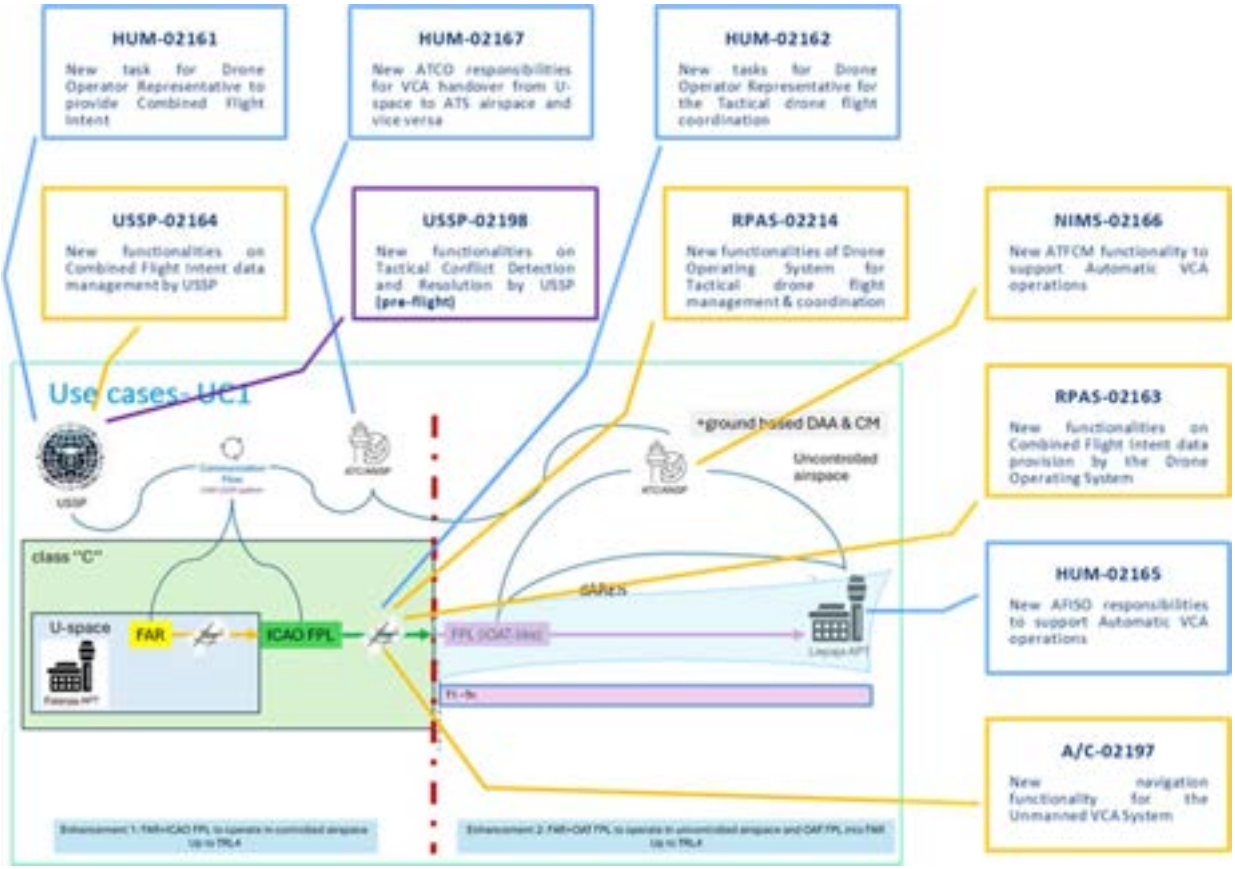


Figure 1. *Results of solution concept – defined and validated enablers*

The executed validation activities of the solution resulted in conclusions on concept clarification, technical feasibility, and recommendations for further research, which may expand operational applicability of the concept and enlarge the IAM aircraft type park. They can support synergy between UTM-ATM and involved stakeholders. Additionally, regulatory and standardization needs were identified, which are reflection on procedural, system and human requirements defined by the solution.

Hydrogen Fuels Cell, Electric and Hybrid Propulsion Aspects for Future Aircraft

Chaired by:
Prof. Carlos Xisto (Chalmers University, Sweden) & Dr. Arne Seitz (Bauhaus Luftfahrt, Germany)

System-Level Modelling of a Recuperative Cathode Air Supply System for a Hydrogen-Fuel-Cell-Electric Regional Aircraft

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1. Introduction / Objectives

Low-temperature proton exchange membrane (LT-PEM) fuel cell systems are a promising option for hydrogen-electric regional aircraft propulsion. Their performance depends on the cathode air supply system (CASS), which must deliver air at the required pressure, temperature, humidity and mass flow across the flight envelope while minimizing weight and power consumption. A turbocharged CASS architecture introduces a tight coupling between system-level operation and the turbomachinery design. The inlet air compressor and outlet air turbine must operate efficiently while remaining within surge, choke and mechanical limits under varying conditions. Recent studies have performed on-design simulations for CASS and system trade-offs for various aircraft types . However, this previous research does not define the optimal design point for the turbomachines. This gap will be addressed by developing a systems-level model of an LT-PEM CASS to derive the turbomachinery design envelope and iterate on the turbomachine design for optimal operation within this envelope.

2. Methodology

A steady-state systems-level model of the CASS was developed. It consists of an air intake filter (F1), that removes large particles before the ambient air enters two parallel centrifugal compressors. The compressed air passes through a filter stack (F2), a recuperative air-to-air heat exchanger (RHEX) transferring heat from the compressor discharge to the air flow leaving the fuel cell. Next, the pressurized air is passed through a liquid-cooled heat exchanger (LHEX) that brings the air to the required humidifier inlet temperature. It is followed by an additional filter stack (F3) and a mass flow sensor for mass flow control. The fuel cell exhaust is passed through two parallel radial turbines to recuperate power. The turbines are equipped with variable nozzle guide vanes to expand their operating envelope. Seal leakage in the compressor and the secondary flow that is taken from the main stream to cool the compressor's air bearings are also taken into account. A schematic of the system is shown in Figure 1.
The compressor and turbine are modelled by means of performance maps. Onset of condensation during turbine expansion was captured by means of an equilibrium method. The heat exchangers are modelled as lumped element models with prescribed fin geometry and using heat transfer and pressure drop correlations available in literature. The filters, mass flow sensor and exhaust duct losses are considered as flow restrictions. The two air off-takes where modelled by means of orifices. The fuel cell stack and its associated humidifier are characterized by thermodynamic inlet and outlet flow conditions. The model is implemented in an acausal simulation environment to enable flexible boundary-condition specification. The model was used to iteratively evaluate compressor and turbine performance for the selected system, starting with initial, estimated component dimensions (e.g. filters, HEXs). Multiple design loops were performed between the model and the turbomachinery designs to ensure consistent matching between component and system-level operation. The model provided key performance parameters, including power, rotational speed, guide vane angle, and pressure ratio across the operating envelope. In addition, full-flight mission simulations were performed to evaluate transient response during operating-point transitions.

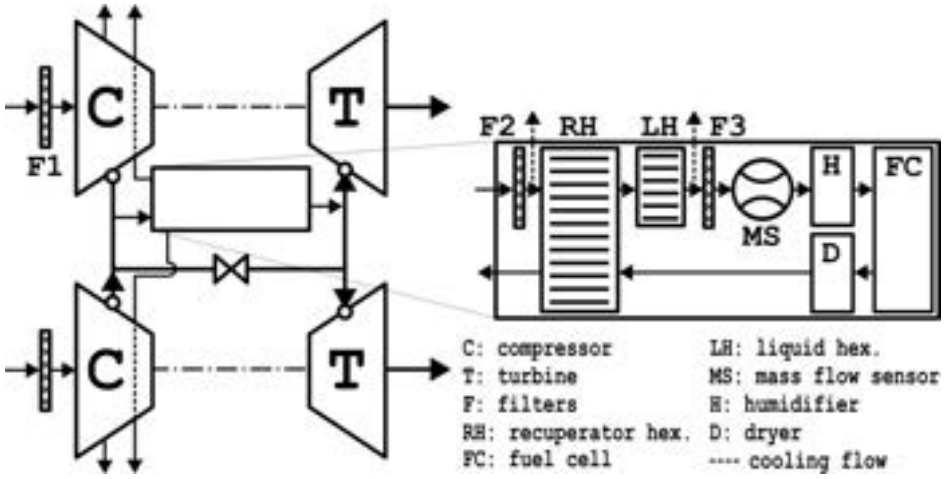


Figure 1. *Schematic overview of the cathode air supply system.*

3. Results / Conclusions

The framework is exercised across a set of key operating points ranging from a sea-level take-off to cruise altitude, a flight mission representative for regional hydrogen-electric aircraft accounting also for different ΔISA conditions. Results provide the required compressor and turbine shaft power, rotational speed, pressure ratio, and variable guide vane positions at each point, defining the operating envelope used as direct input for the next iteration of the turbomachinery design process. Minor condensation is observed at low-temperature, low-power ambient conditions, with limited impact on turbine work. The proposed architecture is shown to operate within stable turbomachinery limits across the full mission, and the work establishes an end-to-end systems-to-component design workflow for future hydrogen-electric propulsion systems.

Test Results for a 500 kW Hydrogen Fuel Cell-Electric Powertrain for Ground Demonstration

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[1] Royal Netherlands Aerospace Centre, Netherlands

[2] Pipistrel Vertical Solutions, Slovenia

[3] Fraunhofer IISB, Germany

1. Introduction / Objectives

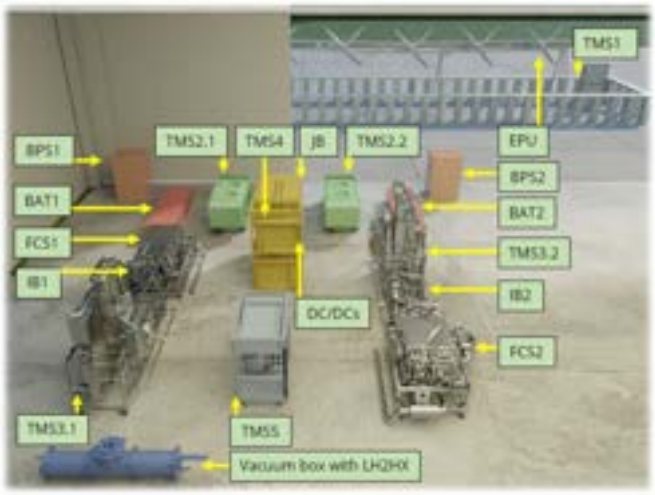
The aviation industry is facing a major transformation with the advent of innovative, sustainable propulsion technologies. Among these, hydrogen-powered fuel cells stand out as a promising solution to reduce the sector's climate impact. The Clean Aviation HyPoTraDe project is at the forefront of this revolution, focusing on the development and testing of a modular, scalable, high-voltage 500 kW fuel cell-electric powertrain. By leveraging waste heat from the fuel cell to condition liquid hydrogen, the aim is to enhance system efficiency. With safety playing a key role, potential powertrain failures are emulated, and mitigations validated. The ultimate goal is to establish a redundant powertrain architecture and garner a comprehensive understanding of modular fuel cell- electric distributed electric propulsion powertrains, thereby contributing to a more sustainable aviation future.

2. Methodology

A 500 kW fuel cell-electric powertrain has been designed and integrated at NLR's Energy to Propulsion Test Facility (EPTF). Figure 1 shows a 3D CAD drawing of the powertrain inside the EPTF. The powertrain is split into two sides, with the left and right parts mirrored to ensure redundancy. Each side consists of a 100 kW fuel cell system and a battery system, with the power transported to a junction box (JB) in the middle of the powertrain. The JB contains four DC/DC converters that boost the voltage from the power sources to a bus voltage of 800 V. The power sources and DC/DC converters are controlled by the Fuel Cell Power Control System (FCPCS) algorithm, which ensures efficient and reliable operation. In normal operation, the power is distributed over motor 1,3 and 6 for one side and to motor 2, 4, and 5 for the other side of the powertrain. The JB contains a crosslinking busbar to distribute the power to the six inverters and motors in case of an emergency. Motors 3 and 4 are an innovative dual motor that drives the middle main pusher propeller. In addition to the propellers as power sinks, the non-propulsive loads of an aircraft are emulated by means of a bidirectional power supply. The bidirectional power supply also emulates the power required to balance plant components of a fuel cell system, such as the compressor at flight altitude. The powertrain includes thermal management systems (TMS) for the individual subsystems, including TMS1 for the motors and inverters, TMS2 for the batteries, TMS3 for the fuel cell systems, and TMS4 for the DC/DC converters. TMS5 is a mechanically pumped two-phase transfer loop (TPTL). The waste heat of the fuel cell system is collected in TMS3 and exchanged in the Interface Box (IB) to the TPTL via a plated heat exchanger. This heat is then transported by the TPTL toward a liquid hydrogen heat exchanger (LH2HX), which conditions the cold liquid hydrogen to the required inlet conditions of the fuel cell systems.

3. Results / Conclusions

The results of the HyPoTraDe project demonstrate the feasibility of a modular and scalable high-voltage 500 kW hydrogen fuel cell-electric powertrain for aviation applications. Key findings include the successful integration and testing of the powertrain, showcasing its potential for efficient and redundant operation as shown in Figure 2. The project's outcomes contribute significantly to the understanding of operational characteristics and failure cases of modular electric powertrains, paving the way for more sustainable aviation technologies.



ACRONYM	SUBSYSTEM
BAT	Battery system
BPS	Bi-directional power supply
DC/DC	DC/DC converter
EPU	Electrical propulsor unit
FCS	Fuel cell system
GH2DS	GH2 distribution system
IB	Interface box
JB	Junction box
LH2HX	Liquid hydrogen heat exchanger
TMS	Thermal management system
TPTL	Two-phase transfer loop

Figure 1. *3D CAD overview of the HyPoTraDe ground test demonstrator inside NLR's Energy to Propulsion Test Facility (EPTF).*



Figure 2. *HyPoTraDe ground test demonstrator inside NLR's Energy to Propulsion Test Facility (EPTF).*

Design methodology for hydrogen-powered hybrid propulsion system architectures for short-range aviation

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1. Introduction / Objectives

Hydrogen has positioned itself as a key fuel in the path towards decarbonization, alongside electrification. However, both technologies still pose significant implementation challenges in aircraft applications . By combining hydrogen with an electric power plant, suitable solutions can be found. For that reason, an e-motor with a propeller configuration using two hybrid architectures is explored: a hydrogen gas turbine and a proton-exchange membrane fuel cell system (FCS), both with batteries. This study proposes a methodology to design and analyze the impact of integrating all hydrogen-based propulsion systems (fuel storage, distribution, and power generation) on short-range aircraft applications.

2. Methodology

In this analysis, various aircraft design systems are evaluated. For this reason, a multidisciplinary optimization platform integrating the different hydrogen-based subsystems was designed. In that regard, a model for each critical aspect was developed and integrated into the evaluation platform, thus including the capability to evaluate and optimize the aerodynamic, the LH2 storage, heat-exchange, power-generation, and energy management (EMS) systems together with their integration into the aircraft structure and the joint simulation of all the subsystems in a representative mission profile. A N2 diagram is shown in, where the algorithm key parameters are correlated.

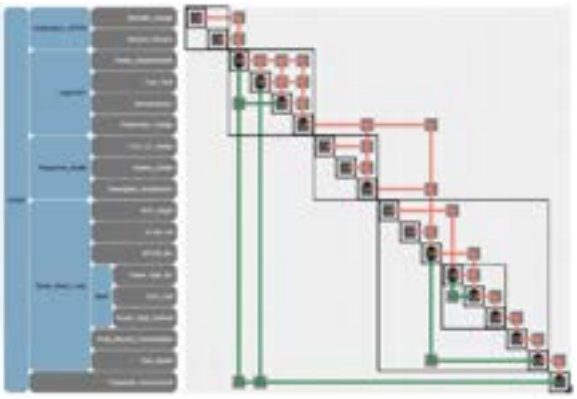


Figure1. *N2 diagram of the self-developed MDAO methodology for hydrogen propulsion systems.*

For the aircraft design, a conceptual design approach was used. The mission target was to transport 72 passengers over 1000 km using short-range aircraft. For that reason, the aircraft was designed using an ATR 72-600 as a baseline and modeled into OpenVSP. All the design methodologies are made following . The hydrogen storage system was set to use liquid hydrogen due to its higher gravimetric density compared to gaseous hydrogen. However, due to its low-temperature requirements, special attention was paid to its isolation. For that reason, a detailed model regarding isolation materials, thickness, and venting strategy was developed following. One key assumption was made regarding the tank: non-integral tanks were selected. They offer lower efficiency but are technically more feasible in the short- to medium-term. The propulsion models were implemented using a tabulated approach. The gas turbine was developed by modifying a generic turbine with representative performance efficiency. The battery was modeled with an equivalent circuit, with a SoC-dependent (state of charge) performance correlation applied in a series and parallel configuration. The FCS was a scaled version of a validated model for automotive applications.
The energy management system (EMS) optimizer in this methodology uses the Pontryagin Minimum Principle to obtain the configuration that minimizes the total energy used in the mission, considering charge-depleting mode from 90% to 85% of the SOC to ensure low recharge times between flights.

3. Results / Conclusions

The optimization analysis shows that hybridization can yield configurations that do not deviate too far from the original design. **Error! Reference source not found.**a shows that the main difference across propulsion architectures is the tank size, which directly depends on fuel consumption. **Error! Reference source not found.**b shows that, while maintaining the desired payload, it is possible to fit a hydrogen GT and an FCS architecture, with increases of 10% and 19% in weight, respectively.

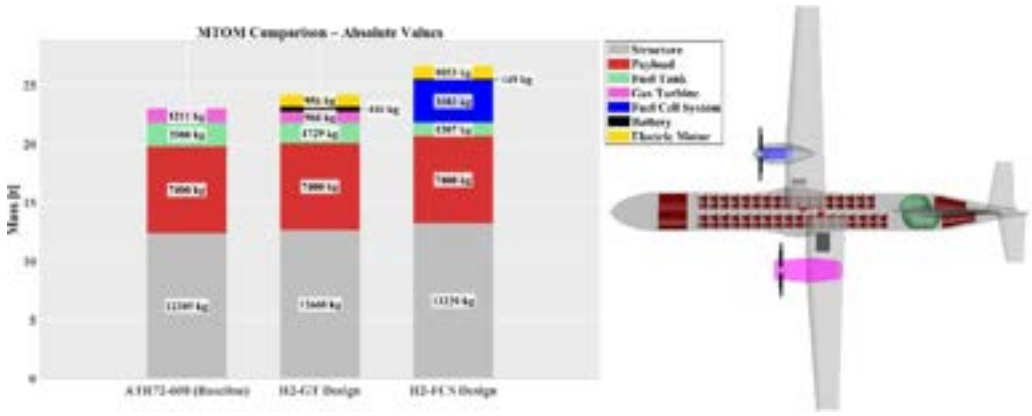


Figure 2. *a) Configuration comparison of GT and FCS architectures b) Weight comparison of proposed architectures with the baseline design.*

On the Implementation and Assessment of the Solid and Permeable Ffowcs Williams–Hawkings Surfaces for Contra-Rotating Open Rotor Aeroacoustics

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1. Introduction / Objectives

In this work, Computational Aeroacoustics (CAA) tools are deployed to predict the noise emissions of a Contra-Rotating Open Rotor (CROR) engine under take-off conditions. While open-rotor architecture offers a viable pathway toward sustainable aviation by drastically lowering fuel consumption, its commercial adoption is strictly bottlenecked by severe acoustic challenges , . High-fidelity aeroacoustic analysis has become an integral component for producing optimal low-noise engine designs, with the Ffowcs Williams–Hawkings (FWH) method dominating across open literature for far-field noise estimation. However, a widespread ambiguity exists regarding the proper implementation, distinct benefits and result interpretation between the solid and permeable boundary types. Consequently, this study investigates the performance and utilization of the FWH formulation to provide clear guidelines for robust numerical simulations. As part of this assessment, both integration surface types are implemented and compared, evaluating critical trade-offs and modelling pitfalls to determine the optimal boundary strategy.

2. Methodology

To achieve this objective, a numerical workflow is established. The transient aerodynamic flowfield is resolved by solving the unsteady Reynolds-Averaged Navier-Stokes (URANS) equations within ANSYS Fluent, using the $k-\omega$ Shear Stress Transport (SST) turbulence model to accurately capture the complex aerodynamic interactions between the two blade rows. To optimize computational resources, a single-passage simulation strategy is adopted. This approach utilizes standard rotational periodic boundary conditions, which are physically justified by the equal blade pitch of the symmetric CROR configuration under investigation. Great emphasis is placed on high-fidelity grid generation within ANSA by BETA CAE Systems to construct a fully structured, hexahedral mesh (Figure 1). To ensure a physically valid aerodynamic foundation, and according to the requirements of the selected turbulence

model, the viscous sublayer is fully resolved by enforcing a wall y^+ value of less than 5 across all blade surfaces, combined with strict grid quality criteria regarding orthogonality and smoothness.

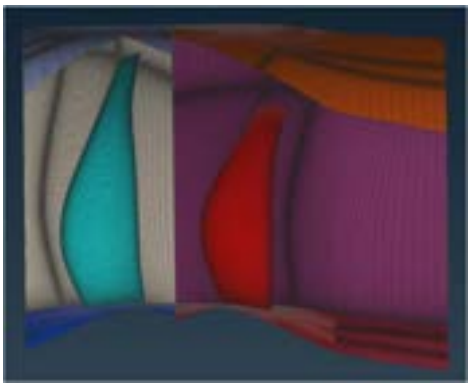


Figure 1. *Near-field shell mesh.*

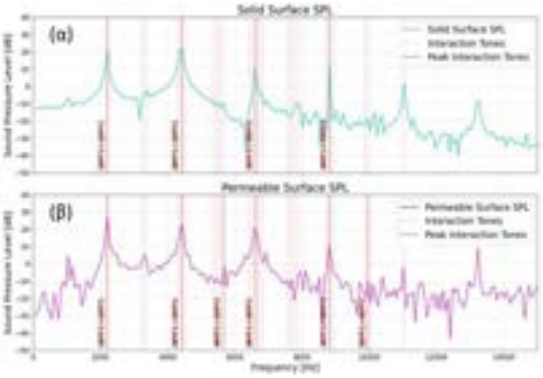


Figure 2. *Noise spectra of Sound Pressure Level (SPL) downstream of the engine through implementing (α) solid and (β) permeable FWH integration surfaces.*

For the far-field aeroacoustic propagation, the Ffowcs Williams–Hawkings acoustic analogy is employed within Fluent. The investigation implements and compares both solid and permeable FWH integration surfaces. The solid formulation extracts source data directly from the rotating blade walls to capture thickness and loading noise. In contrast, the permeable formulation utilizes a virtual enclosure surrounding the blade rows to capture volumetric noise sources. To ensure the integrity of the permeable surface data, sufficient grid resolution is maintained all the way to the integration boundaries to prevent numerical dissipation of the acoustic waves, while the surface is also strategically extended downstream of the engine to mitigate spurious noise from the wake crossings. Finally, far-field noise is computed downstream of the CROR engine, where the spurious noise effect is more pronounced.

3. Results / Conclusions

The extracted noise spectra downstream of the CROR engine demonstrate that both methodologies capture the dominant tonal peaks at interaction frequencies (Figure 2). However, the permeable formulation yields noticeably higher tonal amplitudes at specific interaction and rotor-alone tones. Given that volumetric noise sources are expected to be minor under subsonic take-off conditions, this tonal amplification is primarily attributed to the periodic wakes crossing through the permeable boundary downstream of the engine. Thus, although extending the surface downstream keeps this spurious noise within reasonable bounds, the sensitivity of the permeable boundary type to this effect is obvious. Ultimately, while the permeable surface formulation accounts for volumetric noise sources, their minor acoustic contribution under take-off conditions does not justify the heightened configuration sensitivities and stringent grid resolution requirements. Consequently, the computationally

efficient solid FWH formulation is recommended as the far more practical engineering approach.

Rechargeable Battery-Integrated Islanded Grid Architectures for Highly Electrified Aircraft

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1. Introduction / Objectives

Future electrified aircraft require significantly increased electrical power generation and distribution capabilities due to partially electrified propulsion, zero-bleed architectures, electrified flight control systems and increasing onboard consumer power demand . Electrification of safety-critical on-board systems and propulsion systems increases reliability requirements, certification, system complexity, fault propagation risks, effort and system integration dependencies.
Previous work introduced electrically separated battery-integrated island grid architectures (Fig. 1). In such architectures, batteries are the key enabling technology to separate propulsion and onboard systems. Since purely battery-powered concepts require impractically high installed battery capacities (especially for long range aircraft), rechargeable operation becomes mandatory. However, rechargeability inherently reintroduces electrical interconnections between otherwise separated systems.
This work proposes rechargeable battery-integrated island grid architectures aiming to preserve electrical separation benefits while enabling continuous recharge operation with improved fault containment, reduced redundancy requirements and simplified certification and system integration.

2. Methodology

This paper presents a conceptual architectural analysis of rechargeable battery-integrated island grid topologies for highly electrified aircraft. Different recharge and energy exchange architectures are investigated regarding fault containment, redundancy requirements, operational robustness, certifiability and scalability.
The proposed architectures electrically separate safety-critical onboard systems from propulsion by introducing battery-integrated island grids as continuously active intermediate power interfaces. Batteries thereby serve simultaneously as energy storage devices and architectural decoupling interfaces between generation and load subsystems.
To enable rechargeable operation while preserving separation benefits, several recharge and distribution concepts are proposed. Dedicated distribution and switching devices prevent direct electrical coupling between generators and safety-critical onboard loads during normal operation. The presented architectures enable selective charging of individual battery modules while the remaining modules continue supplying onboard loads. Depending on the selected operating mode, faults occurring on load-side or generation-side interfaces are restricted to individual battery modules or limited battery subsets.
Additionally, dynamically reconfigurable battery systems and battery-integrated modular multilevel converter concepts are discussed as enabling technologies. Furthermore, battery-integrated converter structures enable direct AC interfacing, improved electromagnetic compatibility, reduced harmonic distortion, scalable high-power recharge capability and enhanced fault isolation functionality.
The proposed concepts are evaluated qualitatively regarding their architectural impact on

system complexity, fault propagation behavior and their impact at overall aircraft design level (weight, volume).

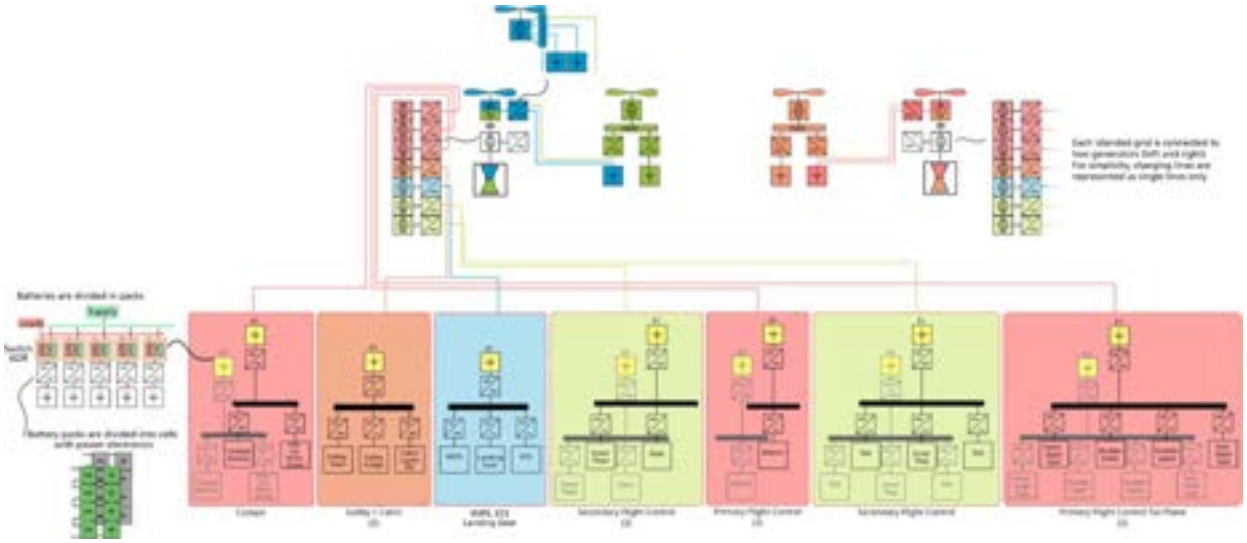


Figure 1. *Electrical System Architecture for Battery Charging.*

3. Results / Conclusions

The presented rechargeable battery-integrated islanded grid architectures demonstrate the potential to maintain electrical separation between propulsion and safety-critical onboard systems while enabling continuous recharge operation during normal aircraft operation.
The proposed concepts provide architectural potential for improved fault containment, simplified fault management, reduced propulsion-side redundancy requirements and reduced electrical coupling between propulsion and onboard systems. Rechargeable operation additionally enables reduced installed battery capacity, thereby supporting future long-range and highly electrified aircraft applications.
Overall, the presented architectures provide a scalable approach for future highly electrified aircraft with potential benefits regarding modularity, certifiability, operational robustness, system integration and high-rate production capability.

Advanced Technologies for Adaptive, Connected and Resilient Satellite Systems

Chaired by:
Prof. Ernestina Cianca & Prof. Ernesto Limiti (University of Roma "Tor Vergata", Italy)

Energy-Aware Opportunistic Connectivity for Earth Observation Satellites Using Commercial LEO Megaconstellation Relays

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University of Rome Tor Vergata, Italy

1. Introduction / Objectives

The rapid deployment of commercial Low Earth Orbit (LEO) megaconstellations is creating new opportunities for providing communication services to independent Earth Observation (EO) satellites. Traditionally, EO missions rely on dedicated ground-station infrastructures for data delivery, often resulting in limited contact opportunities and increased operational costs. Emerging commercial constellations offer the possibility of a Relay-as-a-Service paradigm, enabling EO satellites to exploit third-party relay networks for data transmission. However, relay availability is inherently intermittent due to orbital dynamics, visibility constraints, and access conditions. This work proposes an energy-aware communication framework that enables EO satellites to opportunistically exploit commercial LEO megaconstellations while accounting for intermittent connectivity , communication uncertainty, and onboard resource limitations.

2. Methodology

The proposed framework integrates geometric access analysis, communication link-budget evaluation, contact-uncertainty modeling, predictive energy management, and onboard data-buffer control . First, relay opportunities between EO satellites and commercial LEO constellations are identified through orbital visibility and coverage analyses. Candidate contacts are then assessed using communication link-budget calculations to determine link feasibility and achievable performance.

To address the uncertainty associated with contact prediction and relay accessibility, the framework incorporates probabilistic models that evaluate the robustness of future communication opportunities. Based on these predictions, a predictive sleep–wake scheduling mechanism is implemented to minimize energy consumption by activating communication subsystems only when relay opportunities are expected to occur.

A Delay/Disruption Tolerant Networking (DTN) architecture is adopted to support communication under intermittent connectivity conditions. The DTN layer manages data storage, buffering, and forwarding operations during communication outages, ensuring reliable delivery despite disruptions. Buffer occupancy is continuously monitored to coordinate data generation, storage, and transmission decisions.

The framework is evaluated through representative EO mission scenarios considering different orbital altitudes and commercial relay constellations. Performance metrics include relay availability, communication opportunities, energy consumption, and onboard buffer utilization. The integrated approach enables a systematic assessment of the feasibility and operational benefits of opportunistic relay services in future interconnected LEO environments.

3. Results / Conclusions

Simulation results quantify the trade-offs among relay availability, communication performance, onboard energy consumption, and buffer occupancy. The analysis demonstrates that commercial LEO megaconstellations can significantly enhance communication opportunities for EO satellites while reducing dependence on dedicated

ground infrastructures. An X-band transceiver for ISL has been considered for the energy consumption model. Furthermore, predictive sleep–wake scheduling effectively decreases energy expenditure without compromising data delivery performance. The DTN-based architecture successfully supports reliable operation under intermittent connectivity conditions, mitigating the effects of communication disruptions. Overall, the proposed framework provides a systematic methodology for evaluating opportunistic Relay-as-a-Service concepts and highlights their potential to improve the efficiency, flexibility, and sustainability of future EO missions operating within increasingly interconnected LEO ecosystems.

Adaptive Repurposing of Spaceborne Imaging Platforms for Non-Earth Observation

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1. Introduction / Objectives

The increasing demand for Space Domain Awareness (SDA) is driving interest in innovative approaches capable of exploiting existing orbital assets beyond their original mission objectives . In this context, Non-Earth Imaging (NEI) offers the opportunity to employ Earth-observation satellites as space-based sensors for the observation and characterization of Resident Space Objects (RSOs). Such an approach can significantly enhance operational capabilities while avoiding the costs and complexity associated with the development of dedicated platforms.

This work presents a software-based framework designed to evaluate the feasibility of NEI missions under an "as-is" requirement, meaning that no modifications to the spacecraft onboard software, or to the ground control center architecture are assumed. The objective is to determine whether existing optical imaging platforms can be adaptively repurposed for SDA applications and to identify the classes of targets that can be effectively observed within the resulting operational constraints.

2. Methodology

The proposed workflow is implemented through the Spacecraft Optical Control and Pointing Engine (SCOPE), a Python-based software engine that integrates ESA GODOT or high-fidelity flight-dynamics computations. The proposed framework combines flight-dynamics analysis, payload performance assessment, and target characterization within a unified simulation environment. The methodology evaluates observation opportunities by considering orbital geometry, line-of-sight visibility, illumination conditions, spacecraft maneuverability, and platform operational constraints. These analyses identify feasible observation windows in which an existing imaging payload can be directed toward a non-Earth target while remaining compliant with mission limitations.

Once feasible opportunities are identified, the optical performance of the payload is assessed through radiometric and image-quality analyses. Specific attention is devoted to the impact of relative dynamics, target range, illumination conditions, and sensor characteristics on the achievable observation quality. The resulting performance envelope is then used to characterize the classes of RSOs that can be detected, recognized, or

identified.
The framework has been implemented as an independent software engine capable of interfacing with existing mission architectures without requiring modifications to onboard software. Validation has been performed using a high-resolution agile Earth-observation satellite equipped with a panchromatic pushbroom payload as a representative case study.

3. Results / Conclusions

The results demonstrate that existing Earth-observation platforms can provide meaningful NEI capabilities when supported by dedicated mission-analysis software. The integrated approach enables the identification of feasible observation opportunities, the evaluation of payload performance under non-nominal operational conditions, and the characterization of observable target populations.
The proposed framework provides a scalable and platform-independent methodology for extending the operational value of existing space assets and represents a practical pathway toward enhanced SDA capabilities without the need for new dedicated spacecraft or modifications to systems already in orbit.

Robustness-Driven Design of W-Band GaN LNAs for Next-Generation Satellite Receivers

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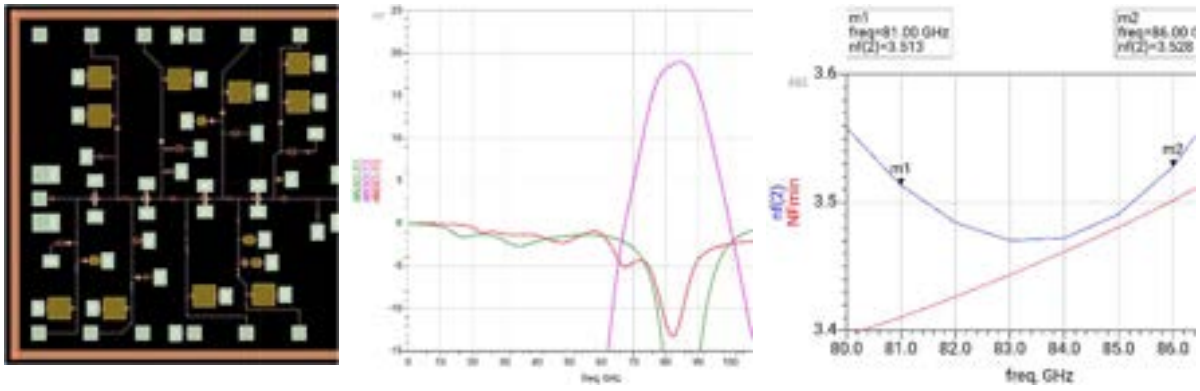
1. Introduction / Objectives

Modern satellite communication payloads in the lower spectrum of the W-band (80–100 GHz) may face a trade-off between sensitivity and survivability. Conventional GaAs-based Low-Noise Amplifiers (LNAs) require input bandpass filters to prevent damage from out-of-band interference and high distribution network losses due to remote placement from the antenna feed. These factors can degrade the overall system G/T.
The objective of this research work is to demonstrate the feasibility of a GaN-on-Si MMIC LNA that leverages the inherent high-breakdown voltage and superior thermal conductivity of Gallium Nitride technology to eliminate or relax input filtering requirements. The innovation in the proposed research activity lies in the systematic characterization of the GaN HEMT Safe Operating Area (SOA) under transient RF conditions, moving beyond conservative CW ratings, often determined for Power Amplifier operation, to establish new design benchmarks for resilient W-band receivers.

2. Methodology

This demonstrator MMIC adopts the D006GH process as the technological platform and aims to design a W-band MMIC LNA meeting the following specifications: maximum noise figure of 3.5 dB (target 3.0 dB), minimum gain of 18 dB in the primary 81–86 GHz band, OTOI of +18 dBm, and the ability to withstand continuous input signals up to +20 dBm for 24 hours. This last requirement effectively rules out any technology other than GaN, making its selection not only competitive but technically mandatory.
The research activity is structured in a sequence steps. First, the state of the art is reviewed,

analysing the evolution of GaN W-band LNAs from 120 nm to more recent 60 nm processes, with particular focus on the MACOM D006GH technology and established design methodologies reported in the literature. The next step addresses active device characterization and selection: parametric simulations in Keysight ADS, combined with the Friis formula, are used to identify the optimal transistor geometry (2×15 µm) at a bias point that provide the best trade-off among noise figure, gain, and linearity. Feasibility with respect to the most critical specifications, namely noise and OTOI, is verified before proceeding. Subsequently, circuit synthesis is carried out, starting from an ideal four-stage topology and progressing to a fully optimized design using PDK components. Input, interstage, and output matching networks, bias networks, and the optimization process—based on Simulated Annealing and Gradient algorithms—are described. The final step includes layout generation, re-optimization under foundry-imposed geometrical constraints, and full electromagnetic simulations using ADS Momentum, providing the most realistic performance assessment.
The final result is a W-band MMIC LNA which, although requiring further post-EM optimization to fully meet specifications, demonstrates the feasibility of the D006GH process for this application and provides a solid design basis for tapeout. The MMIC's layout and simulated linear and noise performance re shown in Figure 1.



(a) (b) (c)

Figure 1 (a) W-band MMIC layout, (b) simulated linear parameters, blue simulated NF MMIC, red simulated NFmin

3. Results / Conclusions

Looking at the work as a whole, two considerations clearly emerge. The first concerns the technology: the MACOM D006GH process has proven to be a competitive platform for W-band LNA applications, confirming the expectations reported in the literature. Finally, a more ambitious direction is the integration of the LNA with power stages within the same process to realize a single-chip monolithic front-end—an objective made technically feasible by GaN-on-Si technology and representing the most promising path for next-generation space and radar applications.

Dual-Band Ku/Ka Low-Noise Amplifier MMIC Development for Future Flexible Satellite Payloads

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1. Introduction

Future flexible satellite payloads require compact RF front-ends supporting multi-band and multi-orbit operation. Concurrent Ku/Ka-band receiver chains are attractive for frequency diversity, traffic reallocation, and fallback operation when one band is degraded. Recent dual-band LNAs have addressed concurrent operation through dedicated matching or noise-matching solutions , , although broadband design approaches are also a possibility . Within this context, the ESA-funded KuKaL activity targets a dual-band Ku/Ka low-noise amplifier front-end for future flexible payloads, with the LNA MMIC identified as a critical building block. The design here discussed addresses the 14–14.5 GHz and 27–31 GHz uplink bands, where simultaneous low-noise and impedance matching is challenging because optimum terminations differ significantly. This work reports a three-stage common-source LNA in 100-nm GaAs pHEMT technology, brought to an advanced stage of development, i.e., schematic level, based on the foundry's process design kit (PDK).

2. Methodology

The MMIC is implemented in the UMS PH10-10 100-nm GaAs pHEMT process, selected for its good balance among noise performance, linearity and space maturity, as well as for the availability of multi-project wafer runs. Device selection was guided by PDK-based small-signal and noise simulations, including source/load terminations, available gain, noise figure, stability margins, and nonlinear constraints around the upper operating band.
In a preliminary phase, several LNA topologies were investigated. This abstract focuses on the selected three-stage source-degenerated common-source architecture, retained as a balanced baseline because it provides sufficient gain, low noise figure, robust stability margins, and comparatively simple RF/DC integration.
The dual-band synthesis is based on four-element matching networks. In their classical use, these networks support broadband impedance shaping . Here, the same degrees of freedom are reinterpreted to control the impedance in two separated frequency bands rather than over a continuous range. The preliminary design follows a conventional left-to-right multistage flow (except that this is applied at two bands simultaneously): each matching network is synthesized to present the selected source termination to the following stage, according to the relevant noise/gain objectives, while the output network provides conjugate matching after the last stage. The complete circuit is then optimized by accounting for gain level and flatness, noise figure, matching, stability, and linearity. Biasing and RF decoupling are included from the beginning of the design procedure to preserve compatibility with a realistic MMIC implementation.

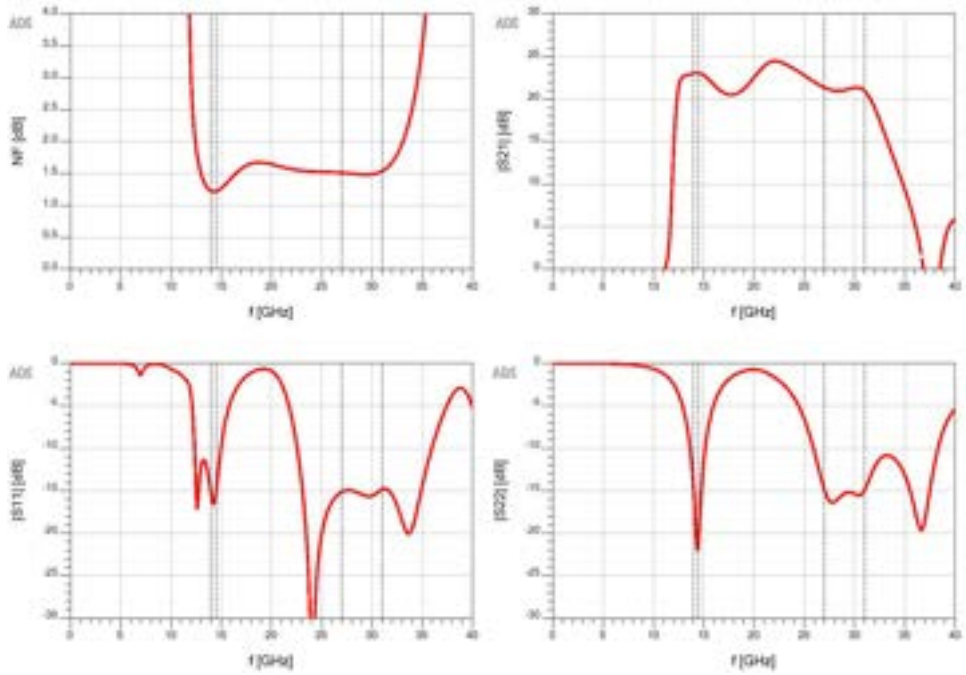


Figure 1. *PDK-based simulations of the small-signal and noise performance of the 3-stage common-source LNA.*

3. Results

The selected three-stage common-source LNA was simulated over the Ku and Ka target bands, namely 14–14.5 GHz and 27–31 GHz. As shown in Fig. 1, the predicted small-signal gain is approximately 20 dB in the lower band and 18 dB in the upper band. The corresponding noise figures are about 1.3 dB and 1.55 dB, respectively. Input and output matching are satisfactory in both bands, and unconditional stability (not shown) is also ensured. These results confirm that the proposed dual-frequency matching strategy enables concurrent Ku/Ka operation without switched or reconfigurable networks. The selected architecture is therefore a solid baseline for the next KuKaL steps, including layout-aware optimization, EM/circuit co-simulation, and integration within the complete receiver front-end.

Integrated Evaluation of Radiation, Thermal and Atomic Oxygen Effects on Structural Materials for Low Earth Orbit Satellite Applications

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1. Introduction / Objectives

Satellites operating in Low Earth Orbit are exposed to harsh environmental conditions. Atomic oxygen, radiation, and thermal cycling can affect the performance of structural materials over time. These effects may cause surface erosion, material degradation, and structural stress. In this study, the combined effects of radiation, thermal loading, and atomic oxygen exposure are investigated for structural materials used in satellite applications. The aim is to evaluate how different materials behave under representative LEO conditions. Radiation

shielding performance, thermal response, and structural durability are considered together. The study also aims to support future material selection studies for satellite structures.

2. Methodology

Representative structural materials used in satellite structures are analyzed under Low Earth Orbit conditions. The study focuses on external satellite panels that are directly exposed to the space environment (Figure 1). The radiation environment is modeled using SPENVIS and OMERE . Trapped proton and electron environments are generated for representative orbital conditions. Radiation transport calculations are then performed using the FASTRAD library . The Reverse Monte Carlo method is used to estimate Total Ionizing Dose levels inside structural regions.

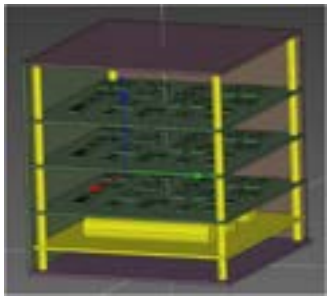


Figure 1. *Satellite panels exposed to LEO environmental conditions*

Thermal and structural analyses are performed within the ANSYS environment . Orbital thermal cycling loads are imposed on the satellite panels to replicate in-orbit environmental variations. The resulting temperature distributions are used as input for structural analysis. Stress fields and deformation responses are then computed to examine the structural response and potential degradation of materials under thermal loading. Stress and deformation behavior are evaluated to examine the structural response and potential degradation of the materials. The coupled analyses allow comparison of thermal behavior, structural integrity, radiation shielding capability, and overall environmental durability for satellite applications.

3. Results / Conclusions

The study provides a comparative evaluation of satellite structural materials under representative Low Earth Orbit environmental conditions. Preliminary findings show that the combined effects of ionizing radiation, atomic oxygen exposure, and thermal cycling can significantly affect both the mechanical stability and long-term performance of materials. The outcomes of this work are expected to contribute to improved material selection strategies for LEO satellite missions.

Analysis of regulation gap and risk for disruptive aviation concepts: CONCERTO methodology

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1. Introduction / Objectives

Innovative aircraft concepts and technologies require a solid set of certification requirements and interpretative material to ensure efficient certification process and timely entry-into-service. For this purpose, the Certification Readiness Level (CRL) scale developed by the Clean Aviation CONCERTO project is a key methodology to assess and measure the readiness of certification regulations and the certifiability of innovative designs. Extending approaches proposed in the literature and complementing previous results from CONCERTO , the presented work delves into methodologies to develop regulatory risk and gap analyses at CRL3 and CRL4 levels, adapted to a large variety of innovations, at different technology readiness levels, and at different aircraft-level integration impacts. This work significantly complements the CRL scale with harmonized criteria to analyze and classify gaps and to formalize orientations for rulemaking activities.

2. Methodology

The work presented in this paper builds upon research conducted within the Clean Aviation CONCERTO project, more specifically the methods developed and applied to assess the certifiability of three innovative aircraft architectures and technologies: hydrogen-powered aircraft, active wing control systems, and hybrid-electric aircraft. Based on these results, the paper proposes generic methodologies addressing the two key phases of the Certification Readiness Level (CRL) scale, namely CRL3 and CRL4. These methodologies aim to standardize the objectives and implementation of regulatory gap and risk analyses, including harmonized criteria to evaluate and classify identified gaps and risks, together with the formulation of rulemaking orientations.

While technological innovations in aviation cover a broad range of configurations and maturity levels, they all share a common requirement: certification by competent safety authorities in accordance with adopted rules. These innovations range from modifications of existing designs to disruptive aircraft architectures, from technologies with high maturity levels to concepts involving major uncertainties, and from innovations with limited certification impacts to those introducing significant and insufficiently characterized regulatory challenges.

Within this context, the proposed approach is based on the in-depth assessment of three technology–certification pairs from CONCERTO project: a modification to an existing design with limited regulatory impact (active wing control), a novel aircraft concept relying on an existing but insufficiently mature certification framework (hybrid-electric aircraft), and a novel aircraft concept involving significant and uncertain regulatory impacts (hydrogen-powered aircraft). Certification specifications involved are EASA CS-25, CS-E and CS-23. Based on

inputs such as concept of operations, risk analysis or preliminary aircraft and/or system Functional Hazard Assessment (FHA), the resulting work leads to the formulation of several approaches for conducting regulatory gap and risk analyses (CRL3), for objectively classifying identified gaps, and for defining associated rulemaking objectives (CRL4), each being adapted to the diversity of certification challenges addressed. It covers in a coherent manner certification requirement, acceptable means of compliance, interpretative material, and standards.

3. Results / Conclusions

The study emphasizes the development of a coherent, structured and quantitative framework to support and strengthen certification readiness assessments conducted through the CRL scale. The presented results were developed and implemented within the CONCERTO project with the involvement of EASA experts. The proposed methodologies and classification criteria are generic and applicable to any technologies and regulatory frameworks in both civil and military domains. They provide essential tools for technology developers and aviation safety authorities, but also for the aircraft design research community particularly for preliminary studies of advanced concepts. These methodologies constitute an important interface between stakeholders to mitigate technical and project risks during a certification program, which is a key factor in achieving timely certification and reducing time-to-market.

Towards Certification by Analysis for Aircraft Systems: Early Insights, Challenges and Opportunities from Initial Research Use Cases

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1. Introduction / Objectives

In order to achieve future sustainable commercial aviation, new aeronautical technologies within aircraft systems are required, but today's certification pathway is long, heavily regulated, and costly—often requiring thousands of ground and flight-test campaigns. These burdens prevent arising technologies from becoming operational within commercial aircraft, due to limited expertise, time, and financial resources. As modelling and simulation (M&S) mature, they offer a means to cut down costly test activities, yet the current regulatory framework only partially embraces M&S and lacks a publicly documented methodology for demonstrating compliance via analysis—known as Certification by Analysis (CbA). This work (i) presents a structured, repeatable CbA methodology that guides applicants through M&S development to compliant documentation, (ii) catalogs scientifically approved analysis methods for each step, and (iii) discusses early insights, challenges and opportunities from early use-case studies. The approach aims to diminish reliance on expensive physical testing and accelerate certification timelines for emerging aircraft systems.

2. Methodology

A comprehensive literature survey was performed, covering standards, guidelines and handbooks from EASA , NASA , IEEE , ASME , SAE , etc. that address verification, validation, model & simulation development, simulation credibility and uncertainty quantification. From these, more than 100 distinct requirements for a CbA framework were extracted and

categorized. Based on these, the herein presented CbA framework was developed that consists of three pillars: Process, Methods, and Documentation.
The *Process pillar* defines a step-wise workflow encompassing first the model concept development, secondly the model design & development including verification and initial sensitivity analysis, thirdly the model validation including the design of validation experiments, the subsequent analysis of a validation metric, the definition of the domain of validation and extrapolation, as well as the final uncertainty quantification for the prediction values of the simulation model. Fourth, the process is ended with the simulation of the certification test procedures.
Within the *Methods pillar*, each process step is linked to a collection of scientifically accepted analysis techniques. They are clearly arranged within a catalogue, so that the certification applicant is guided not only what to do next, but also how to perform each CbA process step.
A collection of templates, prescribing the content, format, level of detail required for each workflow step is provided within the *Document pillar*. The templates ensure that all collected and required information from the CbA process using the proposed methods is documented in a consistent, auditable and structured manner.
The individual steps of the framework are demonstrated using two use cases as examples. One example is an electromechanical actuator for primary flight control. This system is used to explain aspects of sensitivity analysis, uncertainty identification and quantification as well as the design of validation experiments.

3. Results / Conclusions

A CbA framework is proposed consisting of a repeatable, structured process, a method catalogue, and a documentation template. Implementing such a framework enables potential where physical testing would otherwise explode in cost, such as boundary-condition studies, and where certification-related tests are performed in early design stages, preventing later expenses and accelerating cycles.
The pilot applications revealed several challenges. First, sensitivity analysis of complex models with hundreds of deterministic and stochastic parameters is computationally demanding and often requires surrogate-based or adaptive sampling. The same applies to uncertainty quantification. Second, validation metrics must capture system-response quantities across multiple locations in the variable-time space. Third, uncertainty quantification becomes critical when models are extrapolated beyond their domain of validation (DoV), where epistemic gaps dominate; UQ strategies differ markedly from those used inside the DoV.

Damage Models at Multiple Length Scales for Virtual Testing and Qualification/Certification by Analysis

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1. Introduction

Even though the use of carbon fibre-reinforced polymers (CFRPs) has increased drastically in the last few years, full exploitation of the benefits of CFRPs is still limited by their susceptibility to subcritical damage mechanisms and the lack of knowledge and predictive capability of the mechanical response and of the complex damage and failure behaviour of composite

materials. This work presents and provides an assessment of previously developed constitutive laws for applicability in the study of disruptive structural technologies for aerospace applications considering different length scales of CFRP analysis.

2. Methodology and Objectives

At the micro-scale, a statistically representative portion of the composite microstructure capturing fibre diameter, volume fraction, spatial distribution, and stochastic variability is defined . This representative volume element (RVE) provides a framework for predicting effective composite properties, analyzing local stress distributions, load transfer mechanisms, and progressive damage initiation. Periodic Boundary Conditions (PBCs) are commonly preferred for homogenization because they guarantee continuity of displacements and tractions across opposing RVE faces without over-constraining the boundary surfaces. The micromechanical system captures the full thermo-mechanical behaviour of the composite material, including curing, cooling, and the resulting residual stress before mechanical loading. Focusing on subcritical damage mechanisms, such as matrix cracking, the fibres in the RVE are assumed transversely isotropic linear-elastic solids, while the matrix is modelled using a high-fidelity constitutive model to properly capture thermo-elastic effects and fracture. Fiber–matrix interfaces are modelled with cohesive elements or cohesive surfaces, enabling the prediction of debonding, slip, and load redistribution. Such framework is particularly suitable for the analysis of leakage phenomena, key in the design and sizing of liquid hydrogen storage solutions.

At the meso-scale, to predict failure of multidirectional laminates, intralaminar damage models require a ply-by-ply discretisation, where each ply is assumed transversely isotropic and must be represented explicitly in the finite element model. Final structural collapse is the consequence of the accumulation of damage in the different plies of the laminate . To model interlaminar damage, zero- or finite-thickness cohesive zone models are commonly used. Recently , the cohesive zone model proposed by Turon et al. was combined with a Coulomb friction law to simulate delamination onset and propagation.

This work presents the latest results on uncertainty quantification (UQ) at the micro-scale and their propagation to the composite homogenised properties. These analyses entail characterisation of the variability (or uncertainty) of all composite properties by considering the variability (or uncertainty) in the micro-scale model inputs, incl. material parameters and composite morphology (fibre volume fraction, fibre distributions, fibre size, etc.).

3. Results and Conclusions

Based on Bayesian inference, RVEs and constituent properties are sampled and submitted for analysis. From the virtual test data obtained, cumulative distribution functions (CDFs) are created for each meso-scale property and compared with the CDFs of the available experimental composite tests for validation. The unknown meso-scale composite properties and their uncertainties are then derived and employed on meso-scale analysis.

A good correlation is obtained between the virtual and experimental CDFs, validating the proposed methodology. Simultaneously, elastic and strength properties such as transverse Poisson's ratios and shear moduli, transverse tensile strength and failure envelope coefficients under cryogenic conditions are successfully derived for application in leakage and laminate failure analysis on liquid hydrogen storage applications. This work, thus, successfully demonstrates application of a hybrid test pyramid for the performance assessment of a disruptive technology for aeronautical applications.

Acknowledgement: This study was performed in the scope of CONCERTO – Construction Of Novel CERTification methOds and means of compliance for disruptive technologies, a project supported by the Clean Aviation Joint Undertaking and its members. Funded by the European Union, under Grant Agreement No. 101101999. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Virtual EMA-Base Modal Validation of the CONCERTO Aircraft Actuation Test Bench.

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1. Introduction / Objectives

Aircraft actuation systems for active load alleviation and flutter suppression require reliable ground-test platforms capable of reproducing realistic structural stiffness, inertia and dynamic coupling before flight-representative validation. Within the CONCERTO project, a dedicated actuation test bench has been developed to support certification-oriented modelling of disruptive aircraft actuation technologies. The objective of this work is to establish a simulation-based modal characterization and pre-test validation methodology for the CONCERTO test bench using a tiered finite-element modelling strategy and Virtual Experimental Modal Analysis. Low-Fidelity and High-Fidelity FE models are developed to capture both global structural dynamics and local stiffness effects, while Virtual EMA is used to optimize sensor placement, simulate FRF-based modal identification and assess mode-shape correlation before physical testing. The main innovation lies in combining high-fidelity structural modelling with virtual modal testing to the experimental campaign and support future extraction of certification-relevant stiffness and transfer-function data.

2. Methodology

The methodology is based on a tiered numerical and virtual-testing workflow developed for the CONCERTO actuation test bench. First, the complete structural assembly was defined from the available CAD geometry, including the primary steel frame, longitudinal and transverse beams, vertical supports, diagonal stiffeners, actuator interface regions, shaft–flywheel inertia subsystem, bearing supports and local compliance elements. Material and mass properties were assigned consistently to reproduce the inertial and stiffness characteristics of the physical test bench.
Different finite-element model fidelities were then developed. A low-fidelity model was created using one-dimensional beam elements for the main structural members, combined with MPC and RBE2 connections to represent load transfer between simplified subassemblies. This model was used for rapid assessment of global dynamic behavior and preliminary identification of bending and torsional modes. A high-fidelity model was subsequently generated using three-dimensional solid elements for the main structural components. Local mesh refinement was applied near bolt holes, interface regions, stiffeners and shaft-support areas, while connection behavior was represented through bonded contacts, rigid-body elements and bush-type elements where compliance was required. Mesh-quality metrics were monitored to ensure acceptable numerical behavior for modal analysis.

Eigenvalue analyses were performed on both FE models to extract natural frequencies and mode shapes over the frequency range of interest. In parallel, a Virtual Experimental Modal Analysis workflow was implemented using the STL representation of the test bench geometry. An initial set of more than 600 candidate surface measurement locations was reduced to 110 virtual sensor positions through spatial redundancy elimination, modal-sensitivity maximization and structural coverage requirements. Multi-input/multi-output virtual excitation was then applied at selected structurally relevant locations, and frequency response functions were computed at the sensor nodes. FRF averaging and peak-picking procedures were used to identify dominant resonances, while modal parameters were extracted from the simulated response.
Finally, the mode shapes obtained from Virtual EMA were compared with the corresponding high-fidelity FE mode shapes using the Modal Assurance Criterion. This correlation step assessed modal consistency, sensor-layout adequacy and the suitability of the numerical model for subsequent physical EMA planning and certification-oriented stiffness and transfer-function studies.



Figure 1. *Iron Bird, CONCERTO Test Bench.*

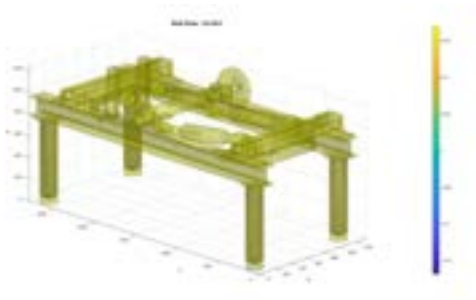


Figure 2. *Iron Bird, Virtual EMA Mode Shapes*

3. *Results / Conclusions*

The modal analyses demonstrated that the CONCERTO test bench exhibits its first elastic global modes in the 19–22 Hz range, with higher modes extending up to approximately 163 Hz. The high-fidelity FE model showed close agreement with the Virtual EMA results across the ten dominant correlated modes, with frequency deviations remaining within engineering-acceptable limits. The first two elastic modes were predicted at 19.50 Hz and 21.32 Hz by the Hi-Fi model and identified at 19.58 Hz and 21.58 Hz through Virtual EMA. MAC values exceeded 0.85 for the correlated modes and were above 0.90 for the principal bending and torsional modes, confirming strong mode-shape consistency and low cross-correlation. These results indicate that the proposed workflow can support pre-test validation, sensor-layout assessment and physical EMA planning. The approach provides a certification-relevant basis for future extraction of actuator anchorage stiffness, transfer functions and aeroservoelastic model inputs.

From Kerosene to Hydrogen: Experimental Foundations for Future Aviation Fire Standards

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1. Introduction / Objectives

The transition toward hydrogen as an aviation fuel presents new fire safety and certification challenges, driven by the unique properties of hydrogen flames and their interaction with aerospace materials. This work builds upon a prior test campaign at low hydrogen flow rates (<1 g/s) and presents complementary experimental results from a second test series conducted at Safran Aircraft Engines with increased hydrogen flow rates (up to 10 g/s). The main objectives of this research are to characterize hydrogen flame behaviour under extreme conditions, evaluate the fire resistance of various materials exposed to these flames, and examine implications for engine integration and certification processes. Technological innovation lies in the systematic study of flame dynamics (including stability, temperature, and heat flux) and material response at higher flow rates not commonly addressed in previous standards or literature. Outcomes provide insight into the adaptation of current fire resistance standards and inform risk assessment strategies for the safe deployment of hydrogen in aviation.

2. Methodology

To comprehensively address hydrogen fire phenomena relevant to aviation, Safran conducted a two-stage experimental campaign: an initial series at low hydrogen flow rates (below 1 g/s) , followed by a second phase at higher flow rates (up to 10 g/s) . This approach enabled the investigation of hydrogen flame characteristics and material responses under both typical and extreme scenarios representative of potential leaks or failures in aircraft engine environments.The tests were conducted at the LEFAE (Laboratoire d'Essais Feux Aéronautiques et Électriques) test facilities in Saint-Chamond, France, using aerospace-grade steel and titanium samples previously qualified by conventional kerosene burner fire standards.

Flames were generated at controlled hydrogen flows, ranging from a reference 0.28 g/s (using a 1 mm diameter nozzle) up to 10 g/s, replicating leak rates from certification scenarios to severe failure cases. To examine the effect of potential leak geometries, multiple nozzle diameters were tested; the distinctive shapes and structures of the flames formed under these different conditions are illustrated in Figure 10.

1mm 0.28g/s	4mm 0.28g/s	8mm 0.28g/s
		

***Figure 10**. Flame shape for three nozzle diameters - at iso-flow rate.*

Both flat plate and cylindrical bar specimens were mounted within the exposure chamber at varied burner-to-sample distances and orientations, allowing investigation into geometric and positional effects on thermal response. The experimental setup, highlighting the configuration

of the specimen and key instrumentation, is presented in Figure 11. This photograph shows a setup replicating, as closely as possible, the conditions of a standard kerosene certification burner for meaningful comparison.

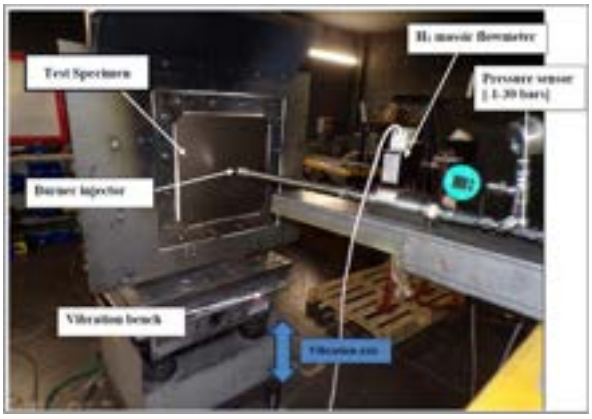


***Figure 11**. Picture of the experimental setup with a specimen mounted in the flame exposure position*

Instrumentation comprised high-temperature thermocouples and heat flux sensors placed at key locations to capture real-time temperature and heat flux evolution, with special attention to sensor placement and mounting given hydrogen's steep thermal gradients. All data from the hydrogen exposures was systematically compared to corresponding kerosene burner tests, facilitating clear benchmarking of flame and material behavior differences. This methodology provided a robust basis for characterizing thermal loads and assessing the fire performance of critical materials under hydrogen exposure, supporting modeling, risk assessment, and standardization efforts for future hydrogen-powered aviation.

3. Results / Conclusions

The study demonstrates that hydrogen flames create distinctly different thermal environments compared to conventional kerosene fires, with higher peak temperatures and significant sensitivity to nozzle diameter and flow rate. Steel and titanium specimens maintained structural integrity under both reference and high-flow hydrogen flames, though localized effects such as surface embrittlement and oxide spalling were observed at the highest exposures. Increased hydrogen flow rates expanded the flame's impact area and favored the formation of central "cold zones," as revealed by infrared thermal imaging, altering thermal constraints across the specimen. These findings underline the need for adapted instrumentation and test protocols when evaluating fire performance under hydrogen exposure. The generated dataset provides a robust experimental foundation for updating fire resistance standards and validates the relevance of reference flame configurations for certification. Overall, this work directly supports risk assessment and modeling for the safe integration of hydrogen in aviation applications.

LCA and LCE in Aviation

Chaired by:
Ms. Ligeia Paletti (German Aerospace Center (DLR), Germany) & Mr. Daniel Kan (Netherlands Aerospace Center (NLR), Netherlands)

Life Cycle Assessment of the HEROPS flying fuel cell

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1. Introduction and Objectives

Clean Aviation aims to mature and demonstrate all relevant elements of liquid hydrogen (LH_2) storage, distribution, and propulsion systems for future hydrogen-powered aircraft. The HEROPS (Hydrogen-Electric Zero Emission Propulsion System) project develops MTU's Flying Fuel Cell™ (FFC) propulsion system for a regional aircraft. This disruptive hydrogen-electric system uses fuel cells as the sole power source with a liquid hydrogen fuel system, eliminating the need for high-power batteries. Integration of both the fuel cell system and electric propulsion unit into a compact engine nacelle ensures high power-to-weight ratio efficiency. HEROPS targets demonstration of a 1.2 MW propulsion system, with scalability to the 2–4 MW power level validated through simulation and testing. The project paves the way for FFC integration on a regional aircraft by 2028 and commercial entry into service by 2035, delivering key propulsion technologies for climate-neutral aviation.

2. Methodology

The goal of this LCA study is to provide a comprehensive comparison of the environmental impacts of two aircraft propulsion systems with an entry into service (EIS) date of 2035: a traditional Jet-A turboprop and the HEROPS Flying Fuel Cell™. The study aims to inform the scientific community and policymakers about the potential environmental benefits and drawbacks of transitioning to hydrogen fuel cell technology in aviation. The results will be publicly disclosed as part of HEROPS's project commitments. Life cycle assessment (LCA) is being conducted in accordance with ISO 14040/44[1], the NLR-DLR LCA in the Air Transport System guidance document[2], and the EF method[3]. The system boundaries consider the airport transport system life cycle as a whole. Figure 1 provides an overview encompassing aviation fuels (Jet-A1 and hydrogen), the aircraft (including materials, components, and operations), and the airport (including infrastructure, operations, and maintenance). For each of these aspects, the life cycle is being examined across raw material extraction, manufacturing, the use phase, and end-of-life. Life Cycle Inventory (LCI) data has been sourced in collaboration with all project partners MTU Aero Engines, MT Aerospace, Collins Aerospace, Eaton, Lufthansa Technik, Technical University Vienna, University of Napoli. Their input has been be instrumental for the LCI data modelling." Ecoinvent[4] is being used for background data on, for instance, Jet-A fuel production. The ESA LCA database is being used for aviation industry-specific materials. Data on fuel burn and direct emissions are obtained from NLR's in-house aircraft mission and design tool[5]. Data on material and energy inputs from hydrogen production, as well as certain direct emissions (such as H_2 purging), are gathered from literature. For the Life Cycle Impact Assessment (LCIA), the EF 3.1 impact assessment method is being applied. The primary impact category is climate change, though all other EF 3.1 impact categories will also be addressed. Adaptations have been made to the IPCC climate model implementation to account for the climate effects of hydrogen emissions and non-CO_2 emissions at altitude.

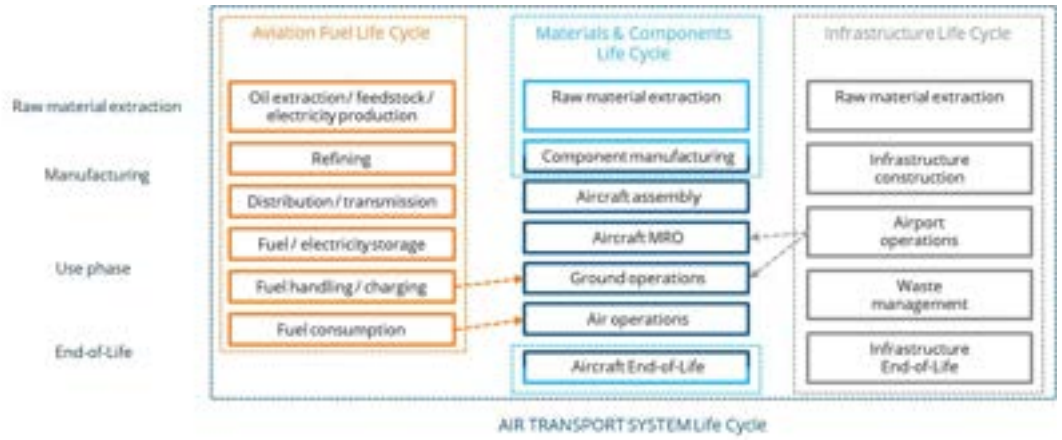


Figure 1. *System boundaries of life cycle assessment in aviation (adapted from Melo et al., 2020[6] & Keiser et al. 2024[7]). Transport and energy use between and within life cycle stages included..*

3. Results & Conclusions

The LCA and LCIA results are expected to yield two types of comparisons between the traditional kerosene-powered aircraft and the hydrogen fuel cell-powered aircraft:

1. A comparison accounting for the full life cycle emissions and resource usage associated with each flight.
2. A comparison covering the manufacturing and EoL of the aircraft and powertrain, excluding other stages

The robustness of the results will be tested through sensitivity and uncertainty assessments.

Acknowledgement: The project Hydrogen-Electric Zero Emission Propulsion System (101140499 – HEROPS) is supported by the Clean Aviation Joint Undertaking and its members.

A combined LCA and noise comparison of transportation modes on five typical intra-European routes

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1. Introduction / Objectives

The primary objective of this Life Cycle Assessment (LCA) study is to compare the environmental impacts of current state-of-the-art transport modes: aircraft, train, passenger

car, and bus. This study aims to complement LCA modelling with noise impact for five intra-European trips. Noise is linked to negative health impacts, and should be included in environmental effects for a more complete analysis. For example, electric cars may have a lower climate impact than petrol cars, but may produce the same amount of noise. While previous studies have incorporated noise into LCA for transport, it has not been used in the context of comparing these transport modes across multiple routes.[1,2] The comprehensive comparison between transport modes will help in understanding the environmental effects of each travel option.

2. Methodology

The functional unit of this LCA study is the transportation of one passenger over a typical intra-European route in a safe manner, using one or more modes of transport, including: a Jet-A1 aircraft, high-speed train, passenger car (petrol and electric), and a fossil-fueled touring bus. The route from Amersfoort (Netherlands) to Rome (Italy) is used as example, and four other routes will also be investigated. A trip may include more than one travel mode, for example traveling by plane requires travel to and from the airport, which is accounted for. The system boundaries encompass manufacturing and material extraction, operation, maintenance, and end-of-life of both vehicles and required infrastructure, fuel and energy production and emissions in use. For noise assessment, the system boundaries are defined along the route during operation. Noise during manufacturing and other phases are out of scope.

Noise is expressed by the number of hindered people, using dose-effect relationships and geographical data to determine number of people affected along the route. The EF 3.1 Impact Assessment method is used for life cycle impact assessment (LCIA), with primary focus on climate change but also addressing other impact categories. Adaptations are made to the IPCC climate model implementation for non-CO_2 emissions at altitude.

Life cycle inventory data will be sourced from databases such as ecoinvent[3] and ESA LCA database[4], complemented by foreground data from literature and expert input, including data on fuel burn and direct emissions of aircraft from the NLR in-house aircraft mission and design tool[5]. Also data from operators will be acquired to ensure accuracy in modelling operations. Regional specific data will be used where possible.

A sensitivity study will assess the effects of variations in assumptions such as vehicle load factors, lifetime of vehicle or infrastructure, use of regional versus hub airport, and travelling to an airport by car versus train. An expected drawback of this methodology is that the route taken will affect the noise impact. To overcome this, the most common route or the suggested route in a route planner will be taken with a potential sensitivity study to assess the effects.

3. Results / Conclusions

Results include a comparison of the five modes of transport for typical intra-European routes, incorporating both LCA and noise modeling outcomes. The LCA results are expected to yield a comprehensive understanding of the environmental impacts of each mode. The study aims to provide LCA results split per life cycle stage for each travel option, including vehicle manufacturing, operation, infrastructure, fuel, and end-of-life, as well as a hinder comparison between travel modes. Sensitivity analysis will be crucial due to the dependency of outcomes on chosen options. This will ultimately contribute to a more holistic understanding of environmental impacts of different transportation modes, aiding in informed decision-making for travelers, policymakers, and researchers. The outcomes will highlight the

environmental drawbacks and benefits of each mode of transport, facilitating a more sustainable approach to transportation.

Introducing a new aerospace-specific life cycle assessment inventory

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[1]ecoinvent Association, Zurich, Switzerland
[2]ETH Zurich, Switzerland

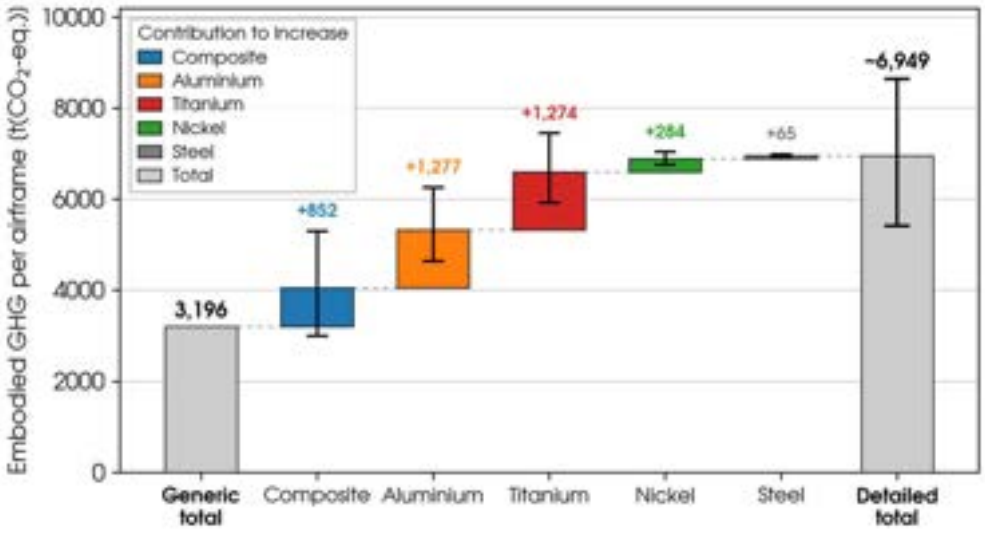
1. Introduction / Objectives

Aviation faces growing pressure to reduce its full environmental footprint. In this context, life cycle assessment (LCA) is the primary tool for informing the eco-design of aircraft as well as sustainability policy. However, the results of an aerospace environmental impact assessment are only as reliable as the life cycle inventory data behind them. To date, most environmental studies have concentrated on the use phase of the aircraft (fuel production and flight operation), while the manufacturing and end-of-life of the airframe itself have been either omitted or reduced to a handful of generic bulk-material datasets. This focus follows an early and recurring finding that the use phase dominates the life-cycle footprint, reaching around 99% of total impact in some assessments , which leaves aircraft production and disposal looking negligible by comparison . The assumption persists in current work. Even in the most comprehensive recent fleet-wide aviation LCAs , the entire airframe is represented as five generic bulk materials and end-of-life treated as negligible. This work therefore quantifies the resulting data gap and argues that aviation LCA must move from bulk-material proxies to aerospace-specific material and process datasets. The shift becomes decisive as airframes turn to carbon-fibre-reinforced polymers, which are energy-intensive to manufacture and neither cheaply nor maturely recycled and as battery- and hydrogen-powered concepts remove the in-flight fuel burn that once overshadowed every other phase, moving manufacturing and end-of-life to the centre of an aircraft's environmental profile.

2. Methodology

Work was carried out within "SMR-ACAP", the Short- and Medium-Range Aircraft Architecture Project of the Clean Aviation Joint Undertaking's SMR pillar (2023–2026), in which ecoinvent leads the development of a dedicated aviation life cycle inventory database. ACAP runs an end-to-end LCA of future SMR aircraft that explicitly covers airframe manufacturing, the industrial system and end-of-life, and aims to replace generic, non-aerospace process data with aerospace-specific industrial datasets suited to prospective assessment of emerging technologies.
First, we characterised how current aviation LCAs represent aircraft production and disposal. Even the most detailed recent fleet-wide studies, such as Sacchi et al. , building on the parameterised fleet model of Cox et al. , reduce the entire airframe to a year-dependent mass fraction of five generic material categories (aluminium, composite, steel, titanium, nickel) applied to the operating empty weight, with the manufacturing processes left implicit

and end-of-life excluded as negligible.
Next, we reconstructed from the model of the implied bill of materials of a representative long-haul airframe and contrast its proxy-based embodied emissions with an aerospace-specific estimate in which each material carries the cradle-to-gate footprint of the finished part rather than of the raw commodity, with uncertainty propagated by Monte-Carlo



simulation. Results are shown in Figure 1.

Figure 1. Preliminary per-material decomposition of the change in airframe embodied emissions when replacing generic bulk-material proxies with aerospace-specific material and manufacturing data. Shown are cradle-to-gate greenhouse-gas emissions of a representative long-haul airframe (operating empty weight ≈ 85 t, 2018 material mix). The left "Generic total" is the proxy estimate (fly-mass × ecoinvent v3.8 material GWP, after Sacchi et al.) while the right "Detailed total" is the aerospace-specific estimate. Waterfall components show material contribution to the increase, evaluated as the cradle-to-gate footprint per kg of finished part, accounting for material grade, manufacturing energy and buy-to-fly losses (stock processed per kg in the part; ≈5–20:1 for titanium). Error bars are 5–95% intervals from Monte-Carlo simulation ($N = 2\times10^5$) with per-step bars describing material marginal contribution uncertainty and the bar on the "Detailed total" giving the full-total interval. Values are illustrative and shown before any scrap-recycling credit.

3. *Results / Conclusions*

For a representative long-haul airframe, the generic proxy yields about 3,200 t CO_2-eq of embodied emissions, apparently dominated by composite. Modelling the same airframe with aerospace-specific materials and manufacturing roughly doubles this to about 6,900 t CO_2-eq (5–95%: 5,400–8,600 t), placing the proxy below even the fifth percentile of the detailed estimate. Figure 1 shows that bulk-material proxies thus do not merely under-count impacts, they misattribute them, undermining the eco-design conclusions that LCA is meant to support. Credible aviation LCA therefore needs aerospace-specific inventory datasets for materials, manufacturing and end-of-life that interoperate with established databases - the exact aim of the aviation life cycle inventory database now being built through the EU Clean Aviation "SMR-ACAP" project at ecoinvent.

A Novel Life Cycle Impact Assessment Method Tailored to Aviation Emissions

Félix POLLET, Thomas PLANÈS
ISAE-SUPAERO, France

1. Introduction / Objectives

Non-CO_2 effects from aviation emissions at altitude represent a major yet insufficiently integrated component of environmental assessments. These effects include climate forcings from contrails, nitrogen oxides (NO_x), water vapour, and aerosols . More broadly, these emissions induce damages on human health via climate change and air pollution (particulate matter and surface ozone formation) , as well as on ecosystems – which are still poorly quantified. Despite better scientific understanding, their consistent integration into life cycle assessment (LCA) through robust characterisation factors is still lacking. Indeed, as of today, LCA studies rely on generic estimates that assume ground-level emissions. Failure to account for altitude effects may introduce significant biases in the environmental assessment of mitigation strategies for aviation.
The objective of this contribution is to address these gaps by (i) proposing a modelling framework to quantify human health and ecosystem impacts of aircraft emissions, (ii) operationalising this framework through the development of characterisation factors linking unit emissions to damages, and (iii) evaluating current and future impacts of global aviation through scenarios.

2. Methodology

The approach combines atmospheric chemistry-transport simulations, climate modelling, and damage functions to capture the effects of emissions at altitude. In addition to characterisation factors applicable to present-day aviation, prospective factors are derived to reflect future changes in atmospheric conditions and population distribution. These factors are applied to aviation scenarios from the International Civil Aviation Organization (ICAO), enabling their assessment beyond a carbon-centric perspective. The simulation of scenarios is performed with AeroMAPS, an open-source Python framework aiming at modelling the air transport transition . The integration of environmental assessments within AeroMAPS is performed using the LCA-Modeller stand-alone package.

3. Results / Conclusions

Some illustrative results obtained for human health are presented (Figure 1). The results indicate that emissions from 2019 international aviation account for a global burden of 2.6 million disability-adjusted life years (DALYs), or 0.5 µDALY per passenger-kilometre. These findings suggest that international aviation contributes 0.3% of global air pollution damages, and 3% of climate-related health impacts from 2019 greenhouse gas emissions. By 2050, under scenarios primarily targeting CO_2 reductions, NO_x are projected to become the second-largest contributor to near-term health damages (100-year horizon), after contrails. However, CO_2 remains dominant over longer time horizons (500-year horizon).

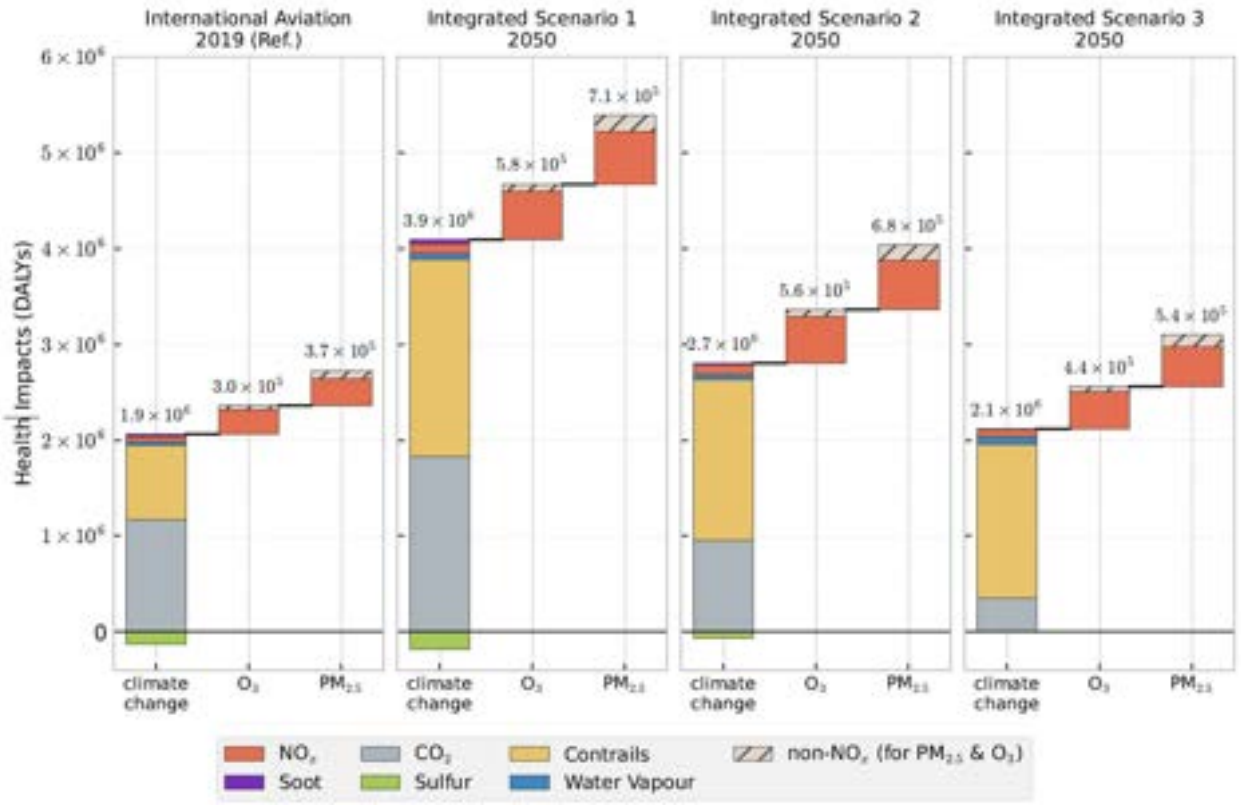


Figure 1. *Health impacts attributable to emissions from international aviation in 2019 and in 2050 under ICAO LTAG scenarios.*

Note that the modelling effort presented is complete (except for ecosystem damages), and that the final application presented to the EASN conference will include several applications, as well as practical recommendations to the LCA community.

Gauging the developments from environmental risk assessment to critical decision support, possibly as life cycle impact assessment, surfaced in simplified life cycle assessment in aeronautics

John Simpson [1], Torsten Moll, Maud Lemagnen
[1]FUTURES ENGINEERING

1. Introduction / Objectives

The aim of the paper is to critically transpose a case study in terms of a simplified LCA (life cycle assessment) into the arena of today's environmental sustainability ontology in as much to analyse state of the art extensions and use for future stewardship of product design processes in aeronautics.

2. Methodology

The treatise handles this matter in position of time and history, physical space and thirdly on adaptivity and adding LCM (life cycle management) accountable value to the product for economic and social actors involved.
It shall provoke a lingering question whether the prospectus of current MBSE (model based scientific engineering) led ontology or more solicited detailing of present engineering is enough to close the gaps or even invent working data for future trade-off analysis; justification for sustainability beyond 2030 or even fourth decade EIS (entry into service) of produced air vehicles or sustaining legacy products.

3. Results & Discussion

As backdrop, a classical use case of competing resources is critically inferred to the level of area of protection (AOP, as implication link) and premise for aggregation of in-time recordable data value, the prospectus of design resolution w.r.t. what it holds in store for characterisation, functionality and normalisation review. Finally, a back of the envelope productivity scoping to help preferencing efficiency or "underwrite" plane or broader product or implication scenarios.

Environmental performance of a single-use PET mandrel for one-piece CFRP air inlet ducts: A comparative life cycle assessment

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1. Introduction / Objectives

The air inlet duct of an aircraft engine is a geometrically complex CFRP component whose mould design strategy strongly influences manufacturing cost, part quality and environmental impact. Conventional production relies on reusable multi-piece aluminium mandrels, or on splitting the duct into two halves moulded on male aluminium tools and subsequent joining. Both routes incur a high tooling mass, energy-intensive aluminium production, and either complex demoulding or an additional joining step. A novel concept replaces the metallic mandrel with a stretch-blow-moulded PET mandrel, shredded and material-recycled after FRP production. This enables the manufacturing of complex one-piece geometries without rigid tooling. The environmental performance of this route relative to established aluminium-based routes has not been quantified. This study compares the three manufacturing routes through a cradle-to-gate LCA in order to identify dominant environmental drivers and inform process selection.

2. Methodology

The study follows ISO 14040/14044 and is performed in openLCA 2.6 with the EF 3.1 indicator set . The functional unit is one finished air inlet duct of identical geometric and functional specification, ready to ship from the factory gate. System boundaries are cradle-to-gate and include raw material production, tooling production amortised per duct over its lifetime in shots, forming and cure energy, process auxiliaries, internal scrap handling and the treatment of production waste. The use phase, transport to customer and end-of-life of the duct itself are excluded. Three product systems are modelled in parallel and compared: (V1) a one-piece duct on a stretch-blow-moulded PET mandrel; (V2) a one-piece duct on a reusable

multi-piece aluminium mandrel; (V3) two duct halves on two reusable male aluminium moulds, subsequently joined. The CFRP laminate uses an amine-cured epoxy matrix on carbon-fibre reinforcement, processed through liquid resin infusion. Background inventories are taken exclusively from the BAFU (ESU) LCI database , with a strict preference for European geographies (RER, fall-back DE/CH/GLO). The database is publicly available and ensures reproducibility and transparency. Proxies are documented when no direct match is available. The PET mandrel system is modelled with a cut-off allocation. Virgin PET production and shredding remain in the system and the recyclate exits burden-free. Aluminium tooling is amortised linearly over its lifetime in shots through parametric expressions, so that sensitivity analyses can be performed without restructuring processes. Allocation is kept identical across all three routes to ensure comparability. Sensitivity analyses are foreseen on tool lifetime, PET mandrel mass and scrap rate.

3. Results / Conclusions

Characterisation under EF 3.1 at a baseline production volume of 300 ducts shows that V1 (PET lost-core mandrel) achieves the lowest environmental impact across all 16 midpoint categories. V2 (aluminium mandrel) follows closely, with climate change approximately 7 % above V1. V3 (two-half bonded) exhibits substantially higher impacts, 85 % above V1, driven by the doubled laminate area and compounded reject rate inherent in the two-piece architecture. Carbon fibre and epoxy resin production dominate climate change in all three routes, accounting for more than 90 % of the total. A supplementary tooling-only analysis confirms that V1 retains the lowest tooling burden despite the single-use PET mandrel, whose mass is too low to outweigh the amortised aluminium production and machining impact. The results demonstrate that the PET mandrel offers a measurable environmental advantage over both aluminium-based reference routes. Figure 1 illustrates these findings.

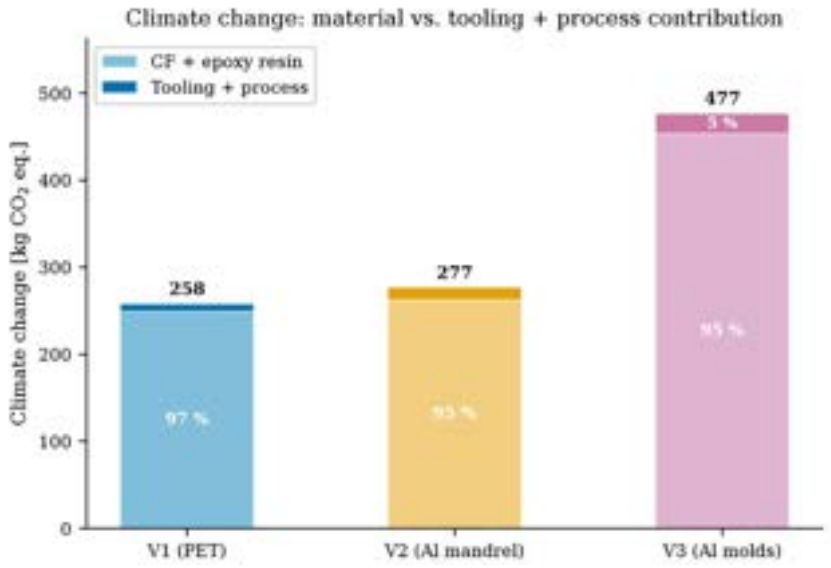


Figure 1. *Climate Change impact of the three assessed manufacturing routes.*

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ecoDESIGN and Life Cycle Assessment for Hybrid Electric Aircraft

Chaired by:
Dr. Thomas Reichert & Mr. Peter Brantsch (Fraunhofer-Gesellschaft, Germany)

Eco-Design and Life Cycle Assessment for Hybrid Electric Aircraft

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1. Introduction / Objectives

The HERA (Hybrid Electric Regional Architecture) is a European project aimed at identifying concepts of regional aircraft able to reduce by 50% the GHG emissions with the use of new technologies. In this way, the novel concepts will be able to satisfy the SRIA (Strategic Research and Innovation Agenda) objective for hybrid-electric regional aircraft.
This instructional presentation will provide an overview of the activities carried out in HERA and linked projects like NEWBORN, HECATE, HERFUSE, HERWINGT, AMBER, HE-ART, etc. to provide a Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) estimation of the proposed concepts.

2. Methodology

Eco-Design aspects linked to HERA activities will be described and the possible implementation in the LCA databases discussed. Simplified LCA and LCC models to support aircraft design for technology and design trade-off and exploration will be mentioned as well as HERA work packages / tasks and linked projects able to provide valuable data for the analysis or direct LCA output.
Data interchanges forms for Life Cycle Inventory data will be introduced and the harmonization of them within Clean Aviation and linked European projects.
Several documents are published for further discussion and decisions proposing the procedure for LCA and environmental footprint declarations.
The eco-design matrix started in Clean Sky 2 will be further extended including the use phase, this enables a holistic and full life cycle view as seen in Figure 1.
Fraunhofer is screening as well published information relevant for eco-Design in aviation for the production and transport of fuels to implement the use phase into the LCA process.

3. Results / Conclusions

The Life Cycle Impact Assessment (LCIA) conducted in the linked projects provided preliminary quantification of the environmental impacts of the hybrid-electric engine's production phase and identified key hotspots.
For example, the LCIA results indicate that the fuel cell stack production represents the most critical contributor within the overall powerplant. This is mainly due to the use of high-impact materials (graphite, fluoropolymers and platinum) in specific parts of the fuel cell power source system. The production of these materials is energy- and resource-intensive and some of these materials are critical for the supply chain.



Figure 1. *Eco-Design and Life Cycle Thinking Approach*

Acknowledgement: These research activities receive supporting funding from the Clean Aviation Joint Undertaking under grant agreement no. 101102007 HERA. This publication reflects only the author's views, and the European Union is not liable for any use that may be made of the information contained therein.

High level LCA of low impact aircraft developed in Clean Aviation HERA project

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1. Introduction / Objectives

In the last decades, civil aviation has been facing new directives regarding the reduction of the environmental impacts during all phases of the aircraft lifecycle. Different European projects are focused on new technologies, and new aircraft designs able to minimize those impacts. In particular, in the framework of the Clean Aviation HERA project, two different aircraft have been developed pursuing different approaches. Hybridization of the propulsion system supplying the electric power train by using only batteries or by using hydrogen fuel cells. Both the innovative aircraft are designed to increase the overall efficiency and to allow the use of Sustainable Aviation Fuel (SAF). This paper describes the results, at aircraft level, of the two approaches in terms of Life Cycle Assessment.

2. Methodology

Perform Life Cycle Assessment (LCA) in the HERA project requires dedicated tool able to operate starting from preliminary aircraft data and able to calculate the environmental

impact of the whole aircraft subsystems and main components. Moreover, it is also necessary to include all life cycle phases such as manufacturing, operation, maintenance and end of life. At Polytechnic of Turin a parametric LCA tool has been developed having in mind the above-mentioned constraints. In particular, the tool is based on a parametric methodology inherited from the cost estimation domain. The environmental impacts are calculated for each aircraft main component (e.g. electric generator, specific avionic equipment, engine compressor stage, wing longeron) assuming materials, manufacturing, assembly and maintenance processes. The LCA estimation is based on Ecoinvent database, and it is calculated to the unity of mass of all items separately. For some components, more than one technology has been accounted to provide some flexibility during the analysis. For example, for structural components such as spare, a spare made of aluminum and composite material are pre-assessed. For batteries, different chemistries are considered; for propulsion system, turboprop and turbofan engines are pre-assessed. Therefore, starting from only high level data coming from the aircraft preliminary design phase it is possible to provide a high level LCA that can be used for trade-off studies of aircraft configuration, system architecture and technologies. The LCA of the operating phase is calculated separately for fuel burning and maintenance. In particular, for the maintenance burden the different maintenance actions, the use of ground facilities and equipment, and the replacement of the components are considered. The end-of-life burden is considered as the sum of the impact of different activities such as the disassembly of the aircraft, subsystems dismantling and the treatment of the hazard materials.

3. Results / Conclusions

The results showed a sensible decrease of Green Houses Gasses (GHG) emitted from the innovative aircraft due to the use of hybrid electric propulsion technology, greater overall efficiency and the use of SAF. The aircraft configuration which employs hydrogen to supply a fuel cell for electric energy generation, it is able to further reduce the impacts with the assumption of using green hydrogen. Another result regards the LCA emissions breakdown. The operating phase represents the main emissions source with respect to the other life cycle phases, especially for what concerns the GHG. The greater part of the impacts comes from the fuel burning; however, maintenance operations also provide a non-negligible impact. In particular, the presence of fuel cells and batteries that have to be constantly replaced during the aircraft life tend to increase.

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Life Cycle Assessment of Aircraft Wing Structures: A Comparative Study of Aluminium and CarbonFibre Composites

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1. Introduction / Objectives

The aviation industry is pursuing clean aviation solutions that reduce environmental impacts across the full aircraft lifecycle. This study applies Life Cycle Assessment (LCA), following ISO 14040/14044, to compare aluminium and carbonfibre reinforced polymer (CFRP) aircraft wing structures using openLCA. The objective is to quantify environmental hotspots and assess whether composite lightweighting can offset higher manufacturing impacts through operationalfuel savings.

2. Methodology

A cradle-to-grave attributional LCA was performed for two functionally equivalent aircraft wings: aluminium and CFRP. The functional unit was one wing operating over a 30-year service life on a representative medium-haul aircraft. The system boundary included raw material extraction, manufacturing, assembly, operation, maintenance,and end-of-life. The model was developed in openLCA using ELCD datasets and literature data. Manufacturing inventories covered primary aluminium production and machining, and for CFRP, carbon fibre production, prepregmanufacturing, lay-up, and autoclave curing. Operational impacts were estimated using a structural mass–fuel coupling model to convert weight differences into lifetime fuel consumption. End-of-life scenarios included aluminium recycling (>90% recovery) and mechanical CFRP recycling. Environmental impacts were assessed using the ReCiPe 2016 midpoint method, focusing on Global Warming Potential (kg CO_2 eq), with sensitivity and Monte Carlo analyses used to evaluate uncertainty.

3. Results / Conclusions

The operational phase dominated total impacts, contributing up to 90% of lifecycle Global Warming Potential. Despite higher manufacturing impacts, the CFRP wing reduced total greenhouse gas emissions by approximately 20.9% compared with aluminium due to lower structural mass and reduced fuel consumption. The results confirm thatlightweight composite wings can provide significant lifecycle environmental benefits and support sustainability-driven aircraft design decisions.

Environmental Impacts of Sustainable Aviation Fuels and Alternative Energy Vectors: Review of existing Life Cycle Assessment data

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1. Introduction / Objectives

Civil aviation currently accounts for approximately 2.4% of global anthropogenic greenhouse gas (GHG) emissions, with liquid fossil jet fuel dominating emissions . Targeting a sectoral 50% emission reduction by 2050 (vs. 2005 levels), Sustainable Aviation Fuels (SAFs) are regarded as

key short/medium-term decarbonization options due to their compatibility with existing aircraft and infrastructure . In parallel, alternative energy carriers, such as power-to-liquid (PtL) fuels, hydrogen and hybrid energy systems, are being considered in the development of new aircraft concepts. Despite their relevance, reported life-cycle GHG emissions for these options vary widely across studies, reflecting differences in system boundaries, feedstocks and methodological choices, among others. Developed within the HERA project, this work aims to critically review and harmonize existing life-cycle assessment (LCA) data for aviation energy vectors providing background data for informed LCA studies and decarbonization strategies.

2. Methodology

A collection of data concerning the impacts of different SAFs was conducted using peer-reviewed literature and internationally recognized default values for aviation fuels and includes well-to-wake and cradle-to-grave GHG emission intensities, expressed primarily in gCO_2eq/MJ, complemented by other units (e.g. $gCO_2eq/seat\text{-}km^{-1}$). SAF pathways reviewed comprise Hydroprocessed Esters and Fatty Acids (HEFA), Fischer–Tropsch (FT), Alcohol-to-Jet (ATJ), Synthetic Iso-Paraffins (SIP), Bio-Electro-Jet Fuels (BEJF), and PtL fuels produced from captured CO_2 and electrolytic hydrogen. Standard jet fuel is used as reference, with emissions hovering at 88-90 gCO_2eq/MJ.

Reported values were compared by grouping results according to feedstock categories and energy supply assumptions (grid mix versus renewable electricity), among others. Special attention is given to the influence of indirect land-use change (ILUC), hydrogen production routes (e.g. hydrogen from steam methane reforming versus electrolysis powered by renewable energy), and the use of different CO_2 capture technologies on overall life-cycle performance. Based on the data, waste-based FT and HEFA pathways may achieve reductions exceeding 70–90% compared to jet fuel, potentially approaching near-zero emissions under favorable assumptions. However, wide variability occurs in terms of emissions when ILUC penalties are applied. To contrast literature with ICAO's benchmarks, CORSIA default life cycle emission factors, including core LCA values and ILUC penalties, are used as reference. Critical stages contributing to GHG emissions are identified, enabling a comparative assessment.

As for PtL, when evaluated, it highlights the importance of electricity's carbon intensity and CO_2 source. While renewable-powered configurations using biogenic or direct air capture CO_2 demonstrate reductions of up to 85–90%, the use of grid mix electricity may negate the reduction altogether. As an example, PtL derived from captured CO_2 (fossil post combustion capture) via Reverse Water Gas Shift presents emissions of 100.8 gCO_2eq/MJ, whereas using renewable electricity lowers the value to 80.3, and changing the captured carbon source to biogenic further lowers it to 10.8 gCO_2eq/MJ, showcasing the importance these factors.

3. Results / Conclusions

The SAF life-cycle GHG emissions span a wide range, from near-zero or net-negative values for residue-based FT fuels integrating carbon capture and renewable-powered PtL pathways, to emissions comparable to or exceeding fossil jet fuel when carbon-intensive electricity, fossil hydrogen, or high-ILUC feedstocks are used. Waste-based FT and HEFA pathways can reduce emissions by 70–90% under favorable assumptions. However, inclusion of ILUC penalties can significantly offset benefits, highlighting sensitivity to land-use assumptions. HEFA derived from waste oils shows robust performance, while crop-based HEFA and ATJ remain highly dependent on fertilizer use and land-use change. For PtL fuels, electricity and CO_2 source, and hydrogen supply are decisive. Green hydrogen produced

via renewable electrolysis is essential to achieving high mitigation levels, whereas fossil-based hydrogen can negate climate benefits. Overall, the energy carriers' environmental impact is dependent on supply or production pathways reinforcing the need for transparent, pathway-specific LCA data.

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Environmental impact assessment of a Fuel Cells Stack in ELECTROPLANE-TEC project

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1. Introduction / Objectives

Within the framework of the ELECTROPLANE research project, funded by the Italian Ministry of University and Research, a Life Cycle Assessment (LCA) has been undertaken to evaluate the environmental impact of key components of a hydrogen-electric propulsion system. Hybrid and fully electric aircraft are increasingly considered promising solutions to mitigate the environmental footprint of the aviation sector. Hydrogen-electric propulsion systems, largely based on proton exchange membrane (PEM) fuel cells, are gaining growing attention due to the high energy density of hydrogen, which enables extended range and increased payload capacity.
While such systems offer the advantage of zero carbon emissions at the point of use, the ELECTROPLANE project also addresses their overall environmental performance by considering the full life cycle of the system components. This includes raw material extraction, manufacturing processes, operational phases, and end-of-life disposal. This study focuses specifically on assessing the total environmental impact of the fuel cell system.

2. Methodology

The applied LCA methodology is based on the guidelines reported in the ISO standards: EN ISO 14040:2006 [01] and EN ISO 14044:2018 [02] and it is devoted to evaluating the environmental impact as well as the potential benefits referring to a reference long term time frame. The assessment has been performed with the support of the commercial SimaPro tool of SimaPro B.V.. To proceed with the LCA analysis, a fuel cell stack was taken into consideration whose characteristics in terms of performance and electrical architecture are publicly available including their specifications in terms of a power level around 30 kW and a voltage of 200 V. The functional scheme of a single fuel cell composed of a cathode, an anode, an electrolyte, and gaskets, it has been analysed. Following the definition of the product tree, each component is quantified with respect to material composition and mass using a material map and the corresponding bill of materials (BoM). A survey has been performed to identify related materials and their chemical composition and physical

characteristics to create a representative catalog of materials including uncertainties and related data sources. The assessment analysis has been performed adopting the IPCC 2021 GWP100, that has been developed by the Inter-governmental Panel on Climate Change (IPCC) and the Environmental Footprint 3.1 method. It contains the Global Warming Potential (GWP) climate change factors of IPCC with a timeframe of 100 years. The calculation has been performed adopting the background information of "Ecoinvent 3" as data library and Industry data 2.0.
Referring to the transport aspects, the means used for the land transport considered have been commercial vans of different sizes, long and short haul and as aircraft categories, belly and dedicated freight aircraft.

3. Results / Conclusions

The performed analysis of the proposed FC stack has provided the related total environmental impact in terms of kg CO2eq as well as the contributions of the FC Stack components and their relevancies. The results clearly highlight that most of the environmental impact is due largely to the chemical species of catalyst cathode, catalyst porous backing layers and catalyst anode. These three elements are representative of 95% of the total environmental impact. A significant contribution to the environmental impact is given by the transportation system used to ship the fuel cell system from factory to the destination.

Environmental impact assessment of the innovative Long-Range Aircraft in EXAELIA project

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1. Introduction / Objectives

In the framework of the Horizon Europe (HE) EXAELIA project [01], life cycle assessment (LCA) activities have been planned to support a holistic impact assessment of the proposed future long-range aircraft (FLRA) concept. Traditional LCA methods (from International Organization for Standardization standards like ISO 14040/44) assume: mature, well-known technologies, stable supply chains and established operational data.
An innovative aircraft (e.g., hydrogen-powered, Saf, novel powertrain…) involves uncertain or missing data, no historical benchmarks, new infrastructures (e.g., hydrogen, SAF production, charging systems), modularity approach and, potentially, the development of testbeds to validate the related environmental impacts.
This paper describes the approach to face this lack of data and consolidated processes adopted to implement LCA for the specific innovative configurations developed in EXAELIA, and it details the LCA activities performed so far for the evaluation of the environmental impacts of EXAELIA disruptive innovations.

2. Methodology

The main goal of this work is to support the validation of the possible environmental benefits achievable thanks to the adoption of FLRA technologies with a strong focus on the systemic implementation of the circularity theme like re-use and recycling of the materials, energy

recovery, prevent resource depletion …. The environmental benefits must be evaluated, in terms of kg CO2eq emissions, environmental footprint related to several impacted categories for long-term effects at aircraft level, used to concur to the validation of the Green House Gasses (GHG) zero-emission.
The applied LCA methodology is based on the guidelines reported in the ISO standards: EN ISO 14040:2006 [02] and EN ISO 14044:2018 [03]. The environmental assessment has been implemented with the support of the SimaPro tool (SimaPro B.V.) to evaluate the environmental impact and the benefits referring to a reference long range model (State of Art at 2024) and a baseline concept representative of the "Business as Usual" in 2050 for the life cycle stages of interest.

3. Results / Conclusions

At the current progress status, the assessment has identified the relevant industrial processes as well as the used raw and semifinished materials, the energy power sources and the transport network involved. The evaluation of the allocation factors through the industrial manufacturing cycles will be described in the paper as well as a synthesis of the preliminary results matured so far.

Life Cycle Data Management in Aviation: Attributional and Prospective LCA approaches – Example of an Aircraft Rudder Material and its Associated Data Gaps

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The aviation research community and industry generate extensive life cycle data across design, manufacturing, operation, and end-of-life phases, yet no standardized overarching approach exists. Available generic databases provide insufficient sector-specific coverage, forcing practitioners to rely on proxy data, introducing uncertainty and limiting cross-project comparability. This fragmentation results in redundant data collection and hinders the industry's ability to meet growing environmental reporting obligations.
This presentation introduces the Life Cycle Assessment (LCA) methodology applied within the Short Medium Range Aircraft Architecture and Technology Project[1] (SMR-ACAP), incorporating data[2] from the Fuselage, Rear Fuselage and Empennage with Cabin and Cargo Architecture Solution validation and Technologies for H2 integration project[3] (FASTER H2) as seen in figure 1.



Figure 1. *Collaborative work from SMR-ACAP and FASTER H2*

The study focuses on carbon fiber reinforced high-performance thermoplastic Polyetherimide comparing Life Cycle Impact Assessment (LCIA) results from attributional (SMR-ACAP) and prospective (FASTER H2) perspectives based on material level. The datasets were modelled using two distinct software environments, LCA For Experts[4] and Brightway[5], exposing considerable challenges related to limited data interoperability and transferability between tools.
Results highlight measurable differences in environmental impact outcomes depending on the methodological scope applied, underscoring the critical importance of aligning goals, system boundaries and data quality standards across LCA in aviation. Key conclusions indicate that the use of simplified life cycle inventories, simplified assumptions and proxy data can potentially mislead decision-makers in technology comparisons and environmental certifications processes. By systematically identifying and analyzing existing data gaps, this study provides validated foundation and a clear motivation for establishing future aviation-specific datasets. Such an approach would reduce methodological redundancy, improve cross-project data reuse and

Acknowledgement: These research activities receive supporting funding from the Clean Aviation Joint Undertaking under grant agreement no. 101101955 SMR ACAP and no. 101101978 FASTER H2. This publication reflects only the author's views, and the European Union is not liable for any use that may be made of the information contained therein.

Screening Life Cycle Assessment of Bio-based Composite Access Panel for Trainer Aircraft:
Environmental Hotspots and Future Circular Pathways

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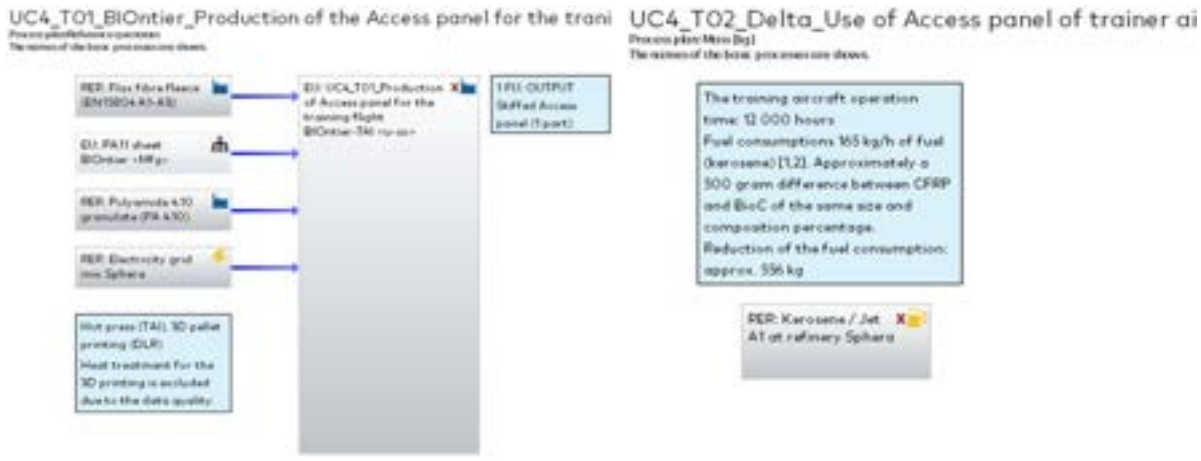
1. Introduction / Objectives

The aerospace industry faces increasing regulatory and market pressure to reduce its environmental footprint while maintaining the rigorous performance standards required for structural and semi-structural components. Bio-based composite materials represent a promising pathway, offering an alternative to conventional fossil-derived or energy-intensive materials such as thermoset carbon fiber-reinforced polymers (TS-CFRP). Within the EU Horizon BIOntier project, a Screening Life Cycle Assessment (LCA) has been conducted to evaluate the environmental performance of a bio-based composite access panel for trainer aircraft. This study quantify the environmental trade-offs of the bio-based BIOntier panel across

production and use phases, identify key environmental hotspots, and explore future circular end-of-life (EoL) pathways.

2. Methodology

The functional unit is defined as one bio-based composite access panel serving the full operational lifetime of the trainer aircraft. The BIOntier solution combines flax fabric with bio-based polyamide 11 (PA11), processed through autoclave-free manufacturing techniques including hot pressing and 3D pellet printing. Compared to the conventional TS-CFRP reference, the bio-based solution achieves a notable reduction in component weight. The Screening LCA is performed using the EF3.1 methodology, covering both the production phase and use phase. (Figure 1. (a), (b)). Background data has been sourced from Sphera and Ecoinvent. Due to the current database limitations, bio-based PA4.10 (approx. 71% biogenic) was used as a proxy for PA11, which in practice reaches close to 100% biogenic content. This substitution is inherently conservative, meaning the actual environmental performance of PA11 is expected to be more favorable than reported here.
As an EoL scenario, a closed-loop recycling strategy is estimated. Production scrap and EoL components made from PA11 based composites can potentially be mechanically recycled, reprocessed into recycled PA11 granules, and used as feedstock for 3D printed stiffener components within the same product system.



(a) LCA model of Production phase (b) LCA model of Use phase

Figure 1. *LCA model of Production phase and Use phase.*

3. Results / Conclusions

Screening LCA results confirm that substituting bio-based feedstock shifts environmental burdens toward land use and freshwater ecotoxicity, driven primarily by the bio-based PA11 and flax fabric inputs. The weight reduction of BIOntier panel yields meaningful fuel savings during the operational lifetime, substantially offsetting the production phase burden and delivering an overall positive environmental outcome. As material-specific PA11 data is refined, these impact categories are expected to reflect a more favorable profile, strengthening the case for bio-based composites in aerospace applications. Minimizing data gaps remains a key priority for the full LCA.

Looking ahead, a closed-loop recycling strategy offers a compelling opportunity to reduce virgin bio-based raw materials dependency and lower the cumulative environmental credentials across the entire product life cycle.

Taken together, these results confirm the environmental feasibility of the BIOntier panel and provide a quantitative basis for bio-based composite integration in future sustainable aircraft design.

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Economic and Environmental Feasibility of Hybrid-Electric Commuter Aircraft

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1. Introduction / Objectives

To fulfil the ambitious net-zero carbon emissions target by 2050, hydrogen has emerged as a viable power source for the aviation sector. While having several advantages over fossil fuels, its adoption imposes fundamental design changes. Moreover, the matter of cost and potential for environmental impact reduction of hydrogen technology will likely dictate which segment they will be profitable. Therefore, there is an imperative to enhance the capabilities of preliminary design tools, namely through increasing model fidelity and augmenting capabilities, to allow for Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). This study presents the implementation of automated cost and environmental impacts assessment within an Overall Aircraft Design (OAD) framework and its application to the assessment of a hybrid commuter aircraft.

2. Methodology

A review of the main open-source OAD frameworks revealed that while considerable work is being done towards the assessment of the feasibility of aircraft with novel powertrains, integrated assessment of cost and environmental impacts, two synergistic approaches, is seldom performed. This study presents the integration in a selected design framework of an

automatic cost assessment as well as an augmentation of an existing LCA module to allow the evaluation of the impacts of hydrogen-based powertrain. Out of reviewed frameworks, the FAST-OAD-GA framework , and more specifically its extension to hybrid-electric powertrain is selected thanks to its extensibility and library of existing models.

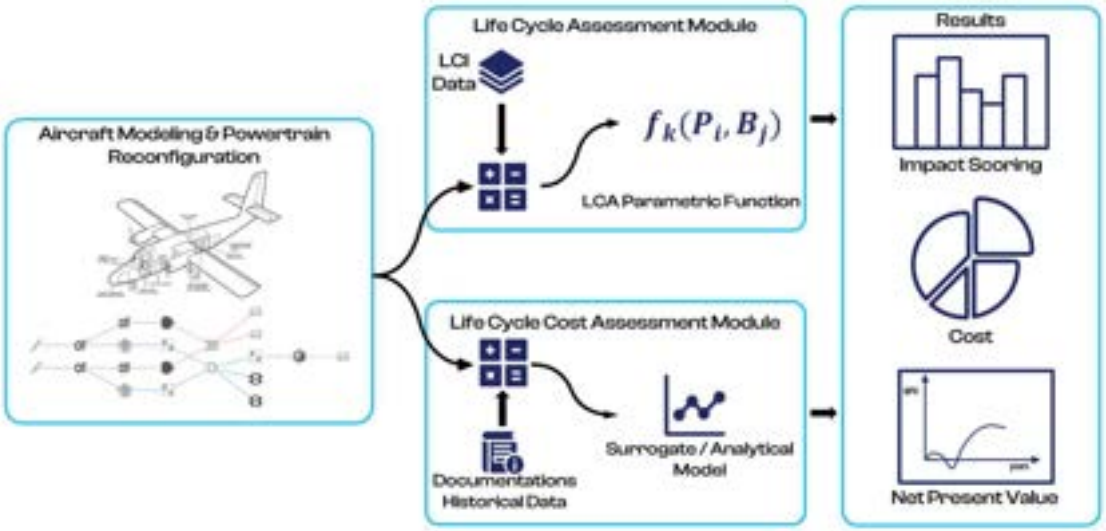


Figure 1. *Schematic view of the study structure .*

The life cycle assessment module proposed in the selected framework is based on the pre-compilation of parametric LCA functions upstream of the design process based on aircraft parameters estimated by other models in the framework. Data collection for these parametric functions is based exclusively on the Ecoinvent database for background processes. The current module version, however, does not include suitable processes to represent the manufacturing of the components in hydrogen-based powertrain nor the production of hydrogen itself. Research was therefore done on the definition of suitable proxies to allow for the assessment of environmental impacts of such configurations.
The newly integrated life cycle cost and net profit value (NPV) module is divided into two aspects for two stakeholders, production phase evaluation for aircraft manufacturers and operational phase evaluation for aircraft operators. The production cost estimation is a combination of the updated Eastlake model and component cost surrogate models. The operational cost is the sum of cost elements obtained from regression models created from documentations, component life expectancies, and market pricing. With calculated costs and estimated revenues, the NPV curves of the aircraft project for both aspects are calculated for financial feasibility estimates.

3. Results / Conclusions

Because of its large operational presence, the DHC-6 Twin Otter is selected as the reference for the implementation of the new assessment modules of hybrid electric feasibility for commuters. Under the assumption of 400 nautical miles range and a cruise altitude of 10,000 ft, the pure hydrogen-powered retrofit carries only 309 kg of payload. Compared with the original 1542 kg payload design, the significant installed weight increase and the cooling drag surge are the major shortcomings for the retrofit design, consistent with previous studies .

Despite these drawbacks, the lower electric component cost reduces the estimated purchase cost of the retrofit by 13%. This result highlights the potential of hybrid configurations to strike a better balance between performance, cost, and environmental impact.

Innovations in Aerospace Propulsion Systems

Chaired by:
Dr. Christos Mourouzidis (Cranfield University, UK)

Integrated Multidisciplinary Assessment of Shaft Power Transfer in a UHBR Geared Turbofan

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[1] Cranfield University, United Kingdom
[2] Rolls-Royce PLC., United Kingdom

1. Introduction / Objectives

Future ultra-high bypass ratio (UHBR) propulsion systems require increasingly integrated multidisciplinary optimisation approaches capable of balancing fuel efficiency, thermal loading, operability, and lifecycle performance simultaneously. Previous studies have highlighted the importance of adaptive cycle concepts, variable geometry, and hybrid propulsion architectures in enabling improved thermal efficiency and operational flexibility for next-generation aero-engines . However, the resulting trade-offs between cruise efficiency, turbine temperature, surge margin, and lifecycle economics remain insufficiently understood, particularly when evaluated across integrated mission and lifing environments. This work presents an integrated workflow linking engine performance simulation, mission analysis tools, geometry sizing and assessment methods, and a life cycle framework to evaluate adaptive geared turbofan architectures under varying power transfer schedules and thermal operating constraints.

2. Methodology

A two-spool geared turbofan model incorporating adaptive power transfer between the intermediate- and high-pressure shafts was developed within a multi-design-point (MDP) Numerical Propulsion System Simulation (NPSS)framework. The MDO cycle design method was based on a fixed 3-point set of thrust requirements for maximum take-off, top-of-climb, and cruise operating conditions. Engine configurations were assessed against multiple competing objectives including minimisation of cruise specific fuel consumption (SFC), reduction of top-of-climb turbine temperatures, and keeping to acceptable surge margins and operability characteristics throughout the flight envelope. The following represent the analysis in this study:

- Parametric sweeps were conducted to evaluate the coupled sensitivity of SFC, core temperatures, pressure ratio split between core compressors, bypass ratio, and engine weight for varying power transfer schedules across operating conditions.

- The down-selected engines were sized, and their weight was estimated, including the necessary power transfer architecture to accommodate the demanded shaft power changes.
- Mission-level performance was evaluated through generated mission decks derived from mission analysis outputs, enabling block fuel and range dependent performance comparisons between configurations.
- Resulting thermal and geometric engine and mission outputs were subsequently integrated into structural and deterministic lifing assessment using Cranfield in-house methods to evaluate creep, oxidation, fatigue, cycles-to-failure trends, and direct operating cost (DOC) implications.

3. Results / Conclusions

The results demonstrate that adaptive shaft power transfer can redistribute thermal loading throughout the mission, delivering substantial lifecycle and operability benefits with near-neutral fuel burn impact. Configurations optimised for reduced top-of-climb turbine entry temperature achieved the highest increase in predicted time-to-failure and in cycles-to-failure with less than a 1% fuel burn penalty on a representative 900 nm mission. In contrast, configurations optimised primarily for cruise specific fuel consumption delivered smaller lifecycle gains despite local efficiency improvements, highlighting the importance of considering thermal loading and durability across the full mission profile.

A balanced power-transfer schedule combining reduced climb thermal loading with improved cruise efficiency achieved an increase in predicted engine life with only a 0.3% increase in mission fuel burn and a modest engine weight penalty. In addition, intermediate-pressure compressor surge margin increased by up to 16 percentage points, alongside improvements in minimum-idle thrust capability, indicating the potential to reduce reliance on traditional operability devices such as the high-pressure compressor blow-off valve. The study demonstrates that significant lifecycle and operability improvements can be achieved through integrated multidisciplinary optimisation, with minimal impact on mission fuel burn, highlighting the value of system-level design approaches for future adaptive UHBR propulsion systems.

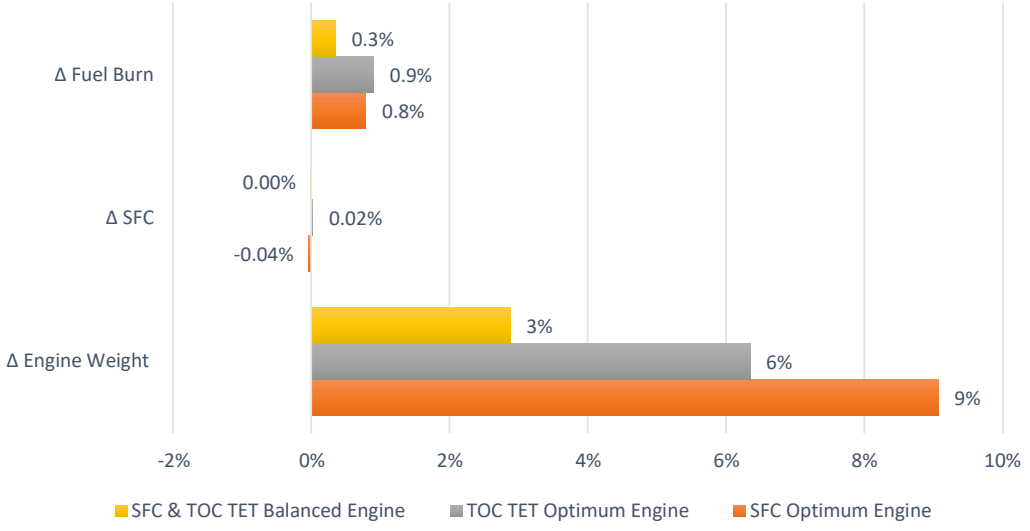


***Figure** 12 Life cycle, Fuel Burn, SFC and Engine Weight Comparison between PT enabled engines.*

Engine-Aircraft Integrated Design for Hydrogen Propulsion, Application to a Family of Small to Medium Range Aircraft

Benoit Said[1], Christos Mourouzidis[1], Pavlos Rompokos[1], Ioannis Roumeliotis[1], Mohamed Aly Abdel-Raheem[2]

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1. Introduction / Objectives

Hydrogen is seen as one of the potential fuels for the small to medium range (SMR) market to mitigate the climate impact of air travel. Numerous studies have investigated storage, propulsion architectures and aircraft configurations. This study focuses on SMR aircraft with a cryogenic tank as it is the most efficient weight-wise, propelled by ultra-high bypass ratio engines.

Since hydrogen is three times lighter per unit of energy but takes about four times more volume than conventional fuels, the impact of these characteristics on the engine cycle design using the multi-design point methodology has not been fully addressed by the current literature . This study therefore builds on previous work on engine-aircraft integrated design and expands on the methodology by increasing the level of fidelity of the aircraft model, allowing for sizing of the wings, the tail and the fuselage, and applies it to a study of a family of aircraft as can be seen in the current SMR market.

2. Methodology

The study is based on an engine-aircraft integrated design framework which combines engine cycle design methods with aircraft sizing methods. The overall framework is set up to iterate and design an engine-aircraft pair able to perform a design mission defined by a number of passengers over a precise range. Here, the main study is carried by using a passenger capacity of 180 and a design range of 2500 NM.

The framework is divided in three main parts:

- An aircraft sizing and performance model is set up using the NASA FLight OPtimisation System(FLOPS). It takes an engine deck, mission parameters (number of passengers and range) and aircraft sizing parameters to size an aircraft for the design mission.
- An engine cycle design model is set up to take as an input three thrust settings and a fan diameter and generates a cycle design using the standard multi design point (MDP) method.
- An in-house code iterates between the aircraft sizing model and the engine cycle design by exchanging thrust requirements and engine decks until convergence is reached over the overall aircraft mass. Additional functions ensure that:
    - The engine mass estimation is performed based on a model calibrated using Cranfield University in house ATLAS framework for engine sizing & weight estimation.
    - The fuselage is lengthened by the appropriate amount to accommodate a cryogenic hydrogen tank, assuming it can occupy the quasi-totality of the cross section of the aircraft in the rear section. The effect of tank gravimetric efficiency/index (GI) was studied by evaluating representative values between 30% and 70%.
    - The wing is placed along the fuselage, and tail areas are sized according to basic stability analysis.

The coupled influence of parameters and technology metrics related to the engine and the aircraft can be evaluated through this framework.

3. Results / Conclusions

Starting from the outcomes of the previous work, a comparison is performed to assess the differences brought by the higher fidelity model as shown on Figure 1.

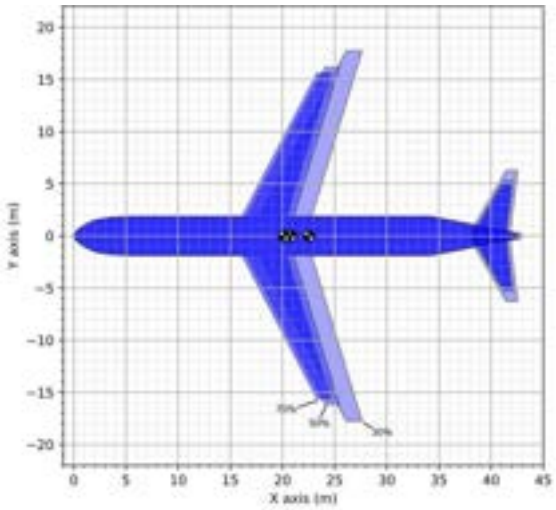


Figure 1. *Top-down view of GI = 30%, 50% and 70% aircraft (fan diameter = 1.85m).*

The framework allows to bring to light the change of the optimal engine as the GI changes. Furthermore, improving the GI brings the take-off and cruise thrust requirements closer, resulting in a higher mid-cruise T40 temperature between 58K and 28K.
Applying the methodology to a different design mission allows to perform a family of aircraft propulsion study. The aim being to identify the trade offs between using a bespoke engine for each aircraft or a common engine for the family. Results show that using the engine from the previous study on an aircraft designed to carry 160 passengers over 2700 NM results in a penalty of 1.2% in SFC and 1.9% in mission fuel burn compared to using a bespoke engine.
The framework presented can carry integrated engine-aircraft technology and design variable assessment for hydrogen aircraft, allowing for quick iteration at the preliminary design stage.

Assessment of Alternative Fuels and Tank Integration Across Aircraft Configurations

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Cranfield University, United Kingdom

1. Introduction / Objectives

The aviation sector's transition towards net-zero emissions requires the evaluation of alternative fuels and their integration within future aircraft architectures. While sustainable aviation fuels (SAF), liquid hydrogen (LH_2), and ammonia (NH_3) offer potential pathways for reducing environmental impact, their implementation introduces significant challenges

related to aircraft configuration, propulsion integration, and fuel storage. This study presents a systematic architectures assessment framework that explores the interactions between fuel type, fuel tank location, and aircraft configurations at the conceptual design stage. A decision-tree-based approach is employed to generate and evaluate a large number of feasible aircraft architectures incorporating different wing arrangements, empennage configurations, propulsion systems, and energy storage solutions. The framework enables automated comparison of conventional kerosene-powered aircraft with alternative-fuel concepts, supporting the identification of promising configuration–fuel combinations based on performance and feasibility criteria.

2. Methodology

The proposed methodology combines architecture enumeration, rule-based feasibility assessment, and performance evaluation within an automated conceptual design framework. Aircraft architectures are generated through a decision-tree approach in which key design decisions are represented as nodes with multiple alternatives. These decisions include fuselage type, wing configuration, wing aspect ratio, empennage arrangement, propulsion system, energy source, propulsion placement, hybridisation strategy, and fuel storage location. Figure 1 illustrates the decision-tree framework used to generate and filter feasible aircraft architectures.

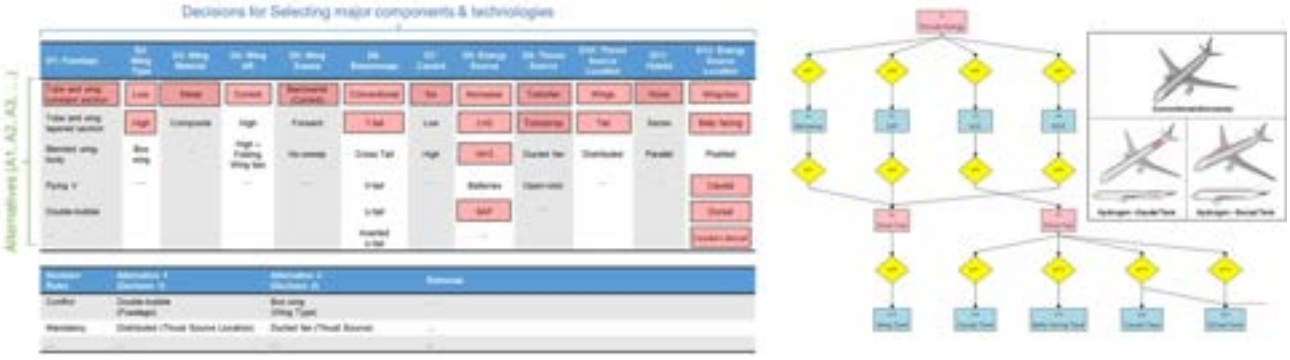


Figure 1. *Decision-tree-based architecture generation and enumeration process*

A set of design rules is applied during architecture generation to ensure only physically feasible and compatible combinations are retained. These rules include conflict constraints, which eliminate incompatible technology combinations, and mandatory constraints, which enforce dependencies between design choices. The resulting framework systematically explores the design space while avoiding unrealistic configurations. Particular emphasis is placed on the evaluation of alternative energy carriers and their associated storage requirements. The study considers conventional kerosene, SAF, LH_2, and NH_3 as candidate fuels. Multiple fuel tank integration options are investigated, including wing-box storage, belly fairings, dorsal tanks, caudal tanks, and combined dorsal–caudal arrangements. The impact of tank placement on aircraft feasibility and performance is assessed across different aircraft layouts.

The architecture generation process produced 72 valid aircraft configurations spanning combinations of low-wing and high-wing arrangements, conventional and T-tail empennages, wing-mounted and tail-mounted propulsion systems, and multiple fuel storage solutions. These architectures are exported automatically to a simulation environment where

performance metrics such as block fuel consumption, passenger capacity, and range capability are evaluated. Figure 2 presents an example of the feasibility assessment results, illustrating the capability of the framework to compare architectures based on mission range and passenger capacity requirements.
The framework enables rapid comparison of a large number of design alternatives and supports architecture down-selection through quantitative performance assessment. By integrating fuel choice, tank placement, and aircraft configuration within a common evaluation process, the methodology provides a structured approach for identifying promising future aircraft concepts.

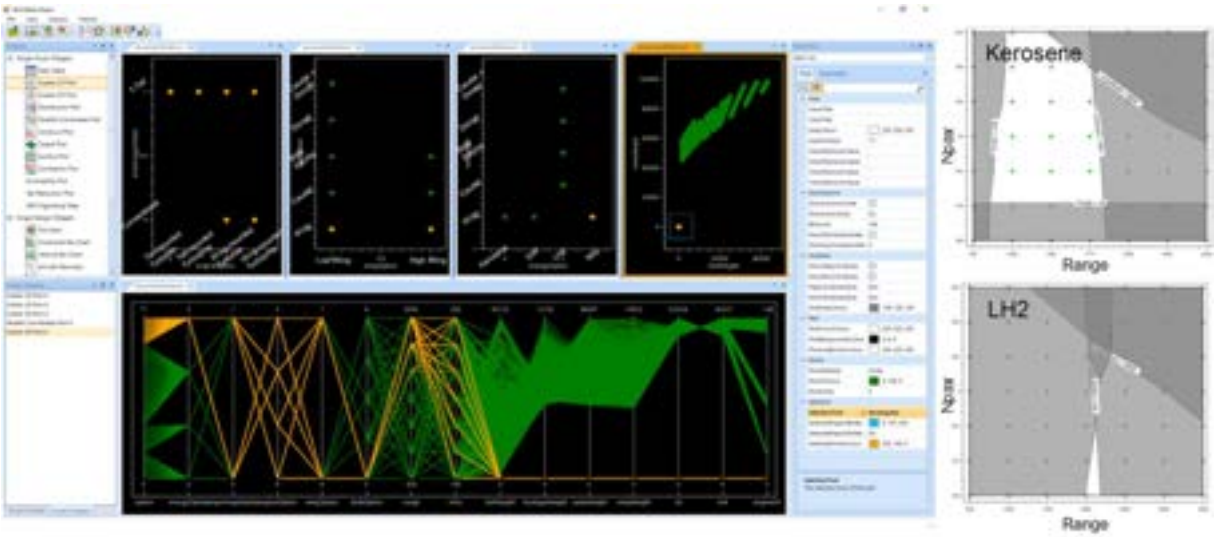


Figure 2 *Feasibility assessment of generated aircraft architectures based on range and passenger capacity requirements*

3. Conclusions

This study demonstrates a systematic framework for evaluating alternative fuels and fuel storage concepts across a wide range of aircraft architectures. The decision-tree-based approach enables automated generation and assessment of feasible aircraft configurations while accounting for compatibility constraints between technologies and design choices. Results show that fuel type and tank integration strategy significantly influence aircraft feasibility and performance, particularly for hydrogen-powered concepts where storage location becomes a key design driver. The framework facilitates rapid exploration of configuration–fuel trade-offs and supports the down-selection of promising architectures for further design refinement. The methodology provides a valuable tool for early-stage assessment of future sustainable aircraft concepts and can be extended to incorporate additional performance, environmental, and operational criteria.

CFD-Based Mission-Level Assessment of Powered Engine Installation Effects for Innovative Medium-Range Aircraft Propulsion

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1. Introduction / Objectives

The Horizon Europe and UKRI-funded MINIMAL project investigates climate-friendly Composite Cycle Engine (CCE) concepts for future sustainable aircraft . Although these propulsion architectures are expected to improve propulsive efficiency and reduce climate impact, their aircraft-level integration may introduce aerodynamic penalties due to larger fan diameters, longer nacelles, and increased wing–nacelle interference. Previous work by the authors assessed nacelle drag increments using a semi-empirical methodology for isolated and interference drag contributions . Building on this foundation, the present work aims to provide a higher-fidelity assessment of engine installation effects on the MINIMAL medium-range (MR) baseline aircraft. The main objectives are: (a) to quantify the aerodynamic impact of representative innovative nacelle geometries under powered-on operating conditions, and (b) to assess how the resulting lift-to-drag ratio variations affect aircraft mission capability in terms of range, endurance, and break-even engine-efficiency requirements.

2. Methodology

The work presented starts with the definition of the MINIMAL medium-range baseline aircraft and representative nacelle geometry variations, including increased diameter, increased length, and simultaneous increase in both.

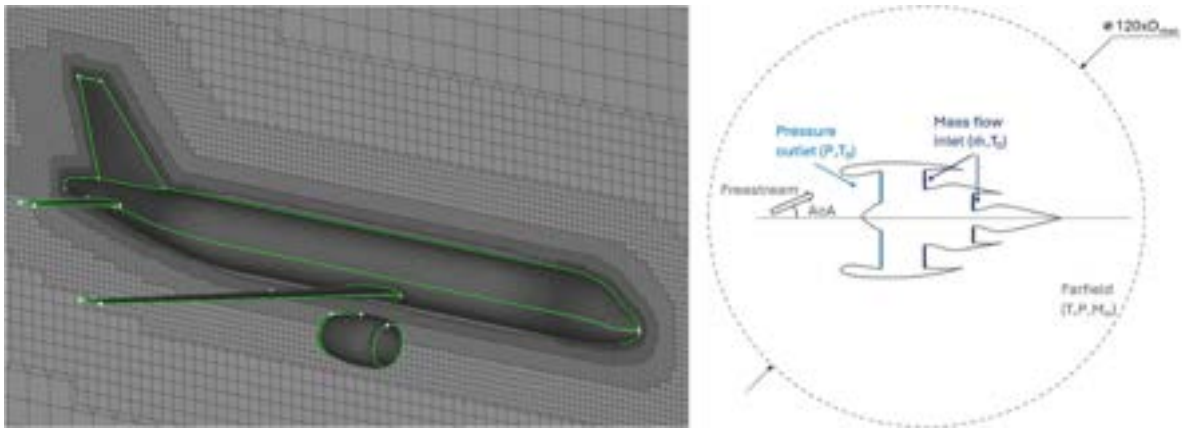


Figure 1. *CFD mesh of the MR and schematic representation of the powered nacelle boundary conditions.*

The next step is the integration of powered-on engine CFD simulations using inlet and exhaust boundary conditions derived from the MINIMAL engine decks, enabling assessment under representative aero-propulsive cruise conditions. The computational mesh and the powered nacelle boundary-condition setup are illustrated in Figure 1. An investigation of installation-position effects is then conducted. The axial and vertical nacelle location relative to the wing are selected as variables, because of their influence on the local pressure field, nacelle-wing

interference, and the resulting installation drag. An evaluation of the CFD results through drag increment, lift-to-drag (L/D) ratio variation, component-level drag breakdown, and nacelle/wing interference effects is then carried out, distinguishing between nacelle-related drag contributions and broader aircraft-level aerodynamic changes. The mission-level indicators are finally evaluated, using a Breguet-based formulation, estimating effects on range, endurance, while a break-even TSFC reduction is introduced, as a means to balance between installation losses and engine efficiency.

3. Results / Conclusions

The expected outcome is an engine-deck-informed CFD assessment of how innovative nacelle geometries and installation positions affect both aerodynamic performance and mission capability of the MINIMAL MR aircraft. The analysis will identify favorable and unfavorable installation regions (Figure 2) and quantify how changes in L/D translate into range and endurance penalties. In addition, the break-even TSFC requirement will indicate the minimum engine-efficiency improvement needed to counter the aerodynamic losses at cruise. The proposed framework links powered-on CFD installation effects with aircraft-level mission performance, providing practical guidance for nacelle positioning and early-stage aero-propulsive integration of sustainable MR aircraft.

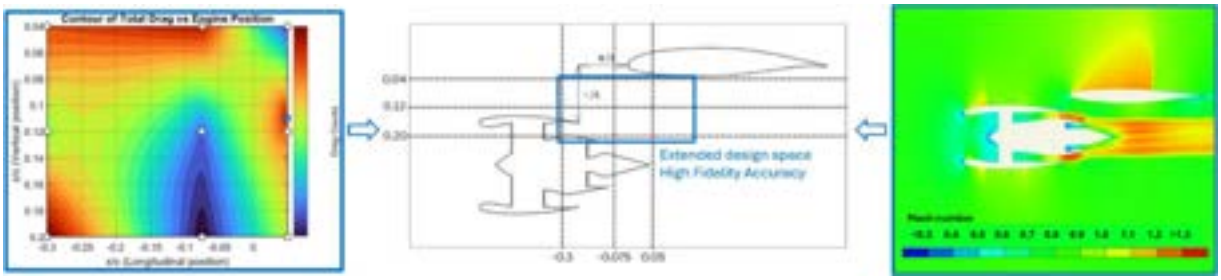


Figure 2. *Nacelle-position design space and powered CFD assessment to evaluate aerodynamic penalties for the MR aircraft.*

Acknowledgement: MINIMAL has received funding from the European Union under the Horizon Europe grant agreement No. 101056863 and from the UK Research and Innovation (UKRI) under contract No.10040930, 10053292 and 10039071. Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor CINEA can be held responsible for them.

Preliminary Sizing, Performance and NOx Reduction Potential of a Hybrid, Hydrogen Gas Turbine Integrated with Solid Oxide Fuel Cells (FlyECO Project)

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1. Introduction and Objectives

Hydrogen Gas Turbines (GT) integrated with Solid Oxide Fuel Cells (SOFC) offer the potential to improve efficiency and reduce NOx emissions for aviation applications. Such a system is being designed and evaluated in the EU-project FlyECO . The SOFC provides electrical power, thus reducing the requirement for fuel consumption in the gas turbine, and is also integrated within the cycle of the GT by receiving air and returning high-enthalpy product gases from the SOFC (Figure 1). Existing literature has mainly focused on energy performance of hydrogen GT-SOFC at design point , assessing off-design performance at a specific operating point for retrofits with hydrocarbon fuels or stationary applications with limited condition or load variations.
This paper evaluates the potential and feasibility aspects of a hydrogen GT-SOFC system for aviation in three areas:

1. Preliminary sizing of a hybrid gas turbine for a clean sheet aircraft design and benchmarking against a reference engine
2. Identification of operating conditions, requirements and constraints throughout the mission profile
3. Analysis of performance gain and NOx reduction potential

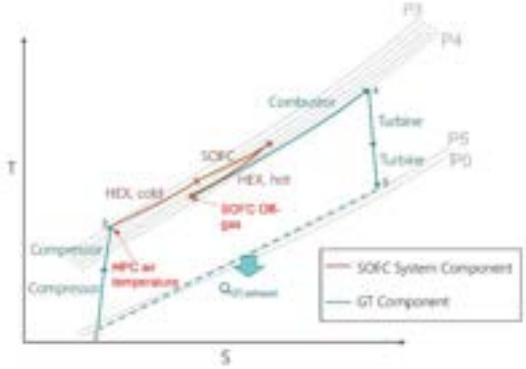


Figure 1. *Hybrid gas turbine cycle T-S diagram (qualitative representation)*

2. Methodology

- The preliminary sizing of the hybrid gas turbine implements component-based, turbomachinery preliminary design methods and receives inputs from the cycle analysis

and performance parameters such as pressure, temperature, mass flow, fuel to air ratio and water to air ratio across the components.
- The performance analysis of the GT considers mission requirements and is performed with an in-house gas turbine performance code, which resolves the thermodynamic cycle, the enthalpy balance, mass continuity and power balance using generic component maps , and incorporates the interfaces and integration constraints with the SOFC system.
- The NOx analysis considers the coupled gas turbine and SOFC performance parameters and uses semi-empirical NOx-emission correlations.

3. Results and Conclusions

- The preliminary sizing of the GT provides dimensions for a mechanical integration model, mass estimate for aircraft-level energy evaluation and inputs for the transient operation analysis, which is a critical challenge of SOFCs for aviation.
- The performance analysis demonstrates that a minimum efficiency gain >10% is possible and establishes the coupling requirements and operability challenges across the flight mission
- The NOx reduction potential analysis provides a preliminary evaluation of how the change in combustor inlet temperature, pressure and steam injection from the SOFC integration impact the NOx emissions.

Acknowledgement: This research has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101138488 and by the UK Research and Innovation (UKRI) funding guarantee under the project reference 10106893.

Objective-Based Energy Management Strategies for Hybrid Electric Propulsion Systems

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1. Introduction / Objectives

Hybrid electric propulsion systems consisting of Jet A/SAF gas turbines and batteries can reduce CO_2 emissions, but can also offer opportunities for operational flexibility. Even within a constant battery capacity selection, the energy distribution across the flight phases strongly affects the gas turbine performance, the sizing of the electric system, the NOx emissions and CO_2 emissions. Literature has mainly focused on data-driven optimisation-based energy management strategies with specific objectives such as the fuel or total energy minimisation. This paper has three main objectives:

1. Formulate distinct energy management strategies based on a power distribution logic among the flight phases.
2. Analyse the energy management strategies in terms of gas turbine performance, sizing of the electric system, gas turbine life consumption, fuel/CO_2 and NOx emissions during specific phases and throughout the whole mission.

3. Characterise the energy management strategies based on their potential for meeting a wide range of objectives.

2. Methodology

The application is a turboprop, regional aircraft with two propellers and is retrofitted with a hybrid electric propulsion system. The framework for the analysis includes the aircraft performance and flight mission base platform, which integrates the propeller, the electric components, the batteries and the gas turbine model. The gas turbine performance output parameters are then input to the NOx emissions model and the gas turbine life consumption model, which includes creep, oxidation and low-cycle fatigue.
A fixed battery capacity (and mass) is set and the available energy is distributed with different strategies across the mission, and the mass of the electric system is sized based on the maximum power arising from each energy management strategy. The strategies include different combinations of constant power or constant degree of hybridisation at different phases, fully electric phases and engine switch off.

3. Results / Conclusions

The energy management strategies are characterised based on outcomes related to total fuel/CO_2, total NOx, airport CO_2, airport NOx, cruise CO_2, cruise NOx and gas turbine life consumption, and the trade-offs in achieving different sustainability objectives are explored, with preliminary findings presented in Figure 1. Finally, fundamental challenges related to gas turbine performance and lifing, as well as the sizing implications of the electric components to cover the energy management strategies, will be discussed. This work will inform the guidelines for the sizing and operation of future, advanced hybrid electric propulsion systems based on priority objectives.

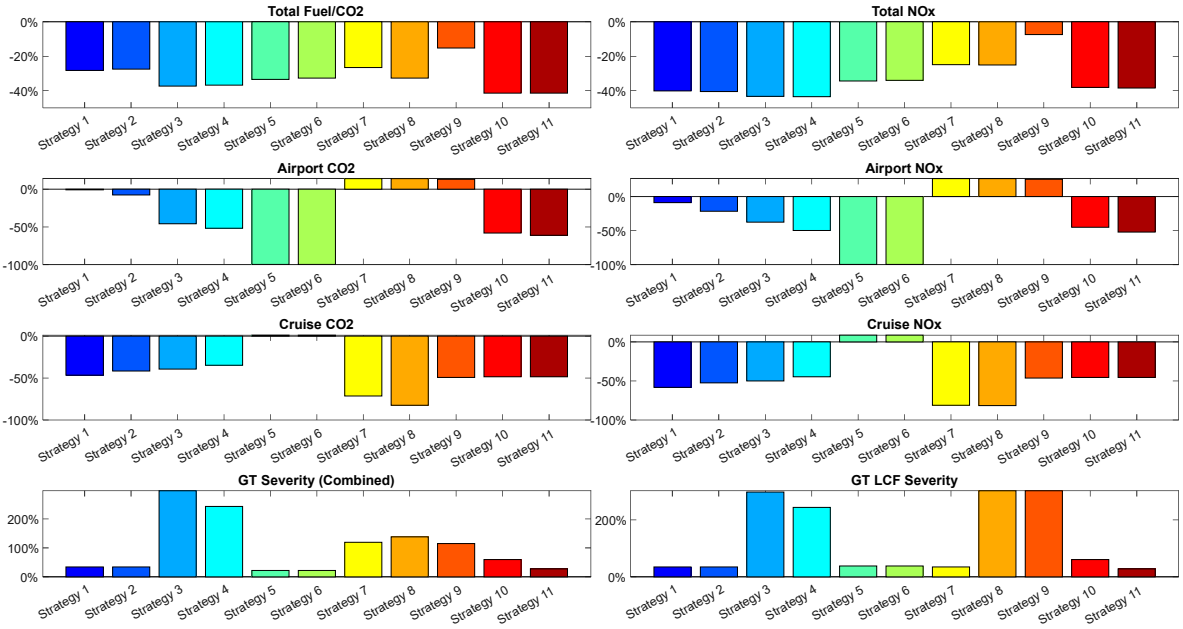


Figure 1. *Variation of fuel/CO_2, NOx and gas turbine life consumption (severity)outcomes relative to the reference aircraft for different energy management strategies*

Operability Analysis and Control Structure Characterisation of a Gas Turbine SOFC Hybrid for Hydrogen-Fuelled Commuter Aircraft

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Cranfield University, United Kingdom

1. Introduction and Objectives

Hydrogen-fuelled hybrid propulsion combining a gas turbine (GT) engine with a solid oxide fuel cell (SOFC) has emerged as a candidate for reducing in-flight emissions on regional aircraft . The architecture analysed in the FlyECO Project , features the SOFC cathode in series of the compressor discharge followed by the GT combustor. The system exhibits a strong bidirectional coupling between the fuel cell operating point and gas generator thermodynamics. Stationary GT-SOFC control has been studied extensively , however the aviation duty cycle introduces qualitatively different constraints including surge margin, turbine entry temperature, transient power demand and the steady state input output structure relevant for control design which has not been systematically characterised for such a topology. This work characterises the foundation of a multivariable Model Predictive Controller. The specific objectives are to: (i) map the operability envelope and constraint activation across representative mission phases; (ii) extract the multi-point scaled steady state gain matrix; and (iii) determine from RGA, SVD and condition number trends the class of multivariable controller required.

2. Methodology

The coupled GT-SOFC model is implemented in MATLAB and calls Turbomatch (Cranfield University Gas Turbine Performance program) for steady-state off-design performance simulation . The GT engine architecture is based on a turboprop with a free turbine sized to 827kW shaft power at take-off (SLS). The SOFC is modelled algebraically using Faraday's law for mass conversions and enthalpy balance for heat rise based on the cell voltage . The manipulated variables considered are Fuel flow, LPC variable stator vane (VSV) angle, HPC VSV angle, air utilisation (AU) for SOFC, fuel utilisation (FU) and cell voltage (U_{cell}) of SOFC; handling bleed is treated as scheduling inputs. The controlled variables are total shaft power, Turbine Entry Temperature (TET), LPC Surge Margin (Z_{LPC}), HPC surge margin (Z_{HPC}), specific fuel consumption, SOFC stack inlet temperature and IPPS Efficiency.
A Latin Hypercube design of 500 samples is generated at the take-off operating point. A Gaussian Process surrogate is fitted to each output and validated against a held-out test set with a normalised RMSE target below 2% on the primary controlled variables. Non-converged samples are used to train a feasibility classifier defining the operability envelope. The analysis is then extended to three operating points spanning the mission envelope (take-off, cruise, top-of-climb). At each operating point, the scaled steady-state gain matrix is extracted by two-sided finite differences using a step size selected from a dedicated convergence study at the baseline. From each Jacobian, the Relative Gain Array RGA, singular value decomposition, condition number, and Niederlinski index are computed for the 6×6 base subsystem. The variation of these quantities across the operating envelope is the evidence base for control-architecture selection.

3. Results and Conclusions

Preliminary analysis at the baseline take-off operating point will quantify the operability envelope and its constraint-activation structure. At each operating point the steady-state

gain matrix together with RGA (as shown in Figure 1 for Takeoff), singular values and condition number is computed. The same analysis is extended to three operating points (take-off, cruise and Top of Climb) to characterise the envelope variation. The expected outcome (based on the physical coupling between AU, surge margin, and the SOFC stack inlet temperature) is the interaction structure which varies with operating point and the constraint activation which shifts between mission phases, both would motivate a multivariable constraint-aware controller over a fixed decentralised architecture.

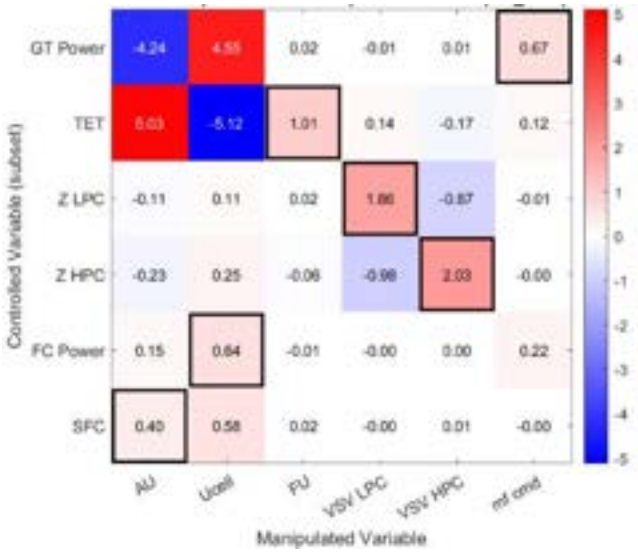


Figure 1. *Relative Gain Array at Take-off (RGAn = 17.8 indicating strong cross-coupling interactions)*

Acknowledgement: This research has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101138488 and by the UK Research and Innovation (UKRI) funding guarantee under the project reference 10106893.

The design of a hybrid turbo-electric propulsion with fuel cells for a hybrid regional aircraft with a capacity of 80 passengers and a range of 1,000 km. An assessment of the effectiveness of integrating fuel cell with a hybrid propulsion system.

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1. Introduction / Objectives

Within the framework of a study to develop a concept for a hybrid regional aircraft (HRA) with a capacity of up to 80 passengers and a range of up to 1,000 km, the concept of a hybrid turbo-electric propulsion system (HTEP) with low-temperature fuel cells using hydrocarbon fuel (kerosene) for the gas turbine engine and hydrogen for the fuel cell, with a system hybridizations level of 20–25%. The results presented are based on research carried out within the framework of the EFACA project (Environmentally clean aviation for all classes of aircraft), financed by the European Commission through the program "Horizon Europe" (Grant agreement No. 101056866), included in the cluster "Climate, energy and mobility".

EFACA aims to promote a greener aviation sector by developing new technologies using electric and hybrid thermoelectric propulsion and new sustainable fuels to combat climate change by 2050 (www.efaca.eu).

2. Methodology

This study employed a step-by-step approach to defining the characteristics of a HTEP, which involved an initial determination of the general requirements for the HTEP and HRA based on an analysis of the current state of the art. In the next stage, conceptual diagrams of the HTEP power supply were developed, along with a preliminary conceptualization of the HTEP components, including their associated subsystems. Subsequently, each result was linked to specific aircraft systems, component operating parameters and performance criteria, and as a result of a comprehensive multi-criteria assessment, the general concept of the HRA-HTEP system was defined.

3. Results / Conclusions

The study focused on the architecture of a HTEP, which consists of a gas turbine engine (GTE) and an electric motor connected by a common gearbox that transmits power to the propeller. The study evaluates the efficiency and weight reduction of a HTEP achieved by utilizing air extracted from the GTE to power the fuel cells, as well as by using water produced as a by-product of the processes occurring in the fuel cells for injection into the GTE. Thus, on the one hand, the water used in the GTE cycle improves its performance, whilst on the other hand; the air supplied from the GTE with the required parameters (pressure and temperature) increases the efficiency of the fuel cell at the flight altitudes of hybrid regional aircraft.

Low-temperature PEM fuel cell air supply system architecture optimization for regional aircraft

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Netherlands Aerospace Centre (NLR), Netherlands

1. Introduction & Objectives

The aviation sector is facing stringent greenhouse gas emissions standards: the ICAO Council and the EU mandate respectively an additional 10% and a target 55% cut in CO_2 emissions by 2030.

Among the H_2-based propulsion systems, low-temperature proton exchange membrane (LT-PEM) fuel cells (FCs) are a compact, efficient and environmentally-friendly solution. Effective LT-PEM operation relies on the cathode air supply system (CASS), delivering pressurized oxygen to the cathode . Recent studies have proposed advanced methods for CASS on-design cycle calculation , optimisation , and system architecture trade-offs for different aircraft types . However, previous research lacks comprehensive CASS design optimisation involving turbocompressor mean-line models and preliminary heat exchanger (HEX) models. This work addresses this gap by integrating a radial turbine model, operating with humid air and nozzle guide vanes (NGV). Two CASS configurations, with and without a recuperator heat exchanger (RHEX) upstream of the turbine, are optimized and evaluated comparatively.

2. Methodology

The steady-state CASS model was developed using the acausal Modelica language. Ambient air enters a scoop intake and an air filter (F1), before being split between two parallel centrifugal compressors. After pressurization, the hot flow, purified in another air filter (F2), is cooled sequentially in the RHEX and the Glycol-Water (GW) liquid heat exchanger (LHEX). Air is then humidified before entering the FC. The humid air leaving the FC is reheated in the RHEX and expanded through two parallel turbines prior to exhaust. All system components are explicitly modelled in an in-house Modelica library, except for the humidifier and FC, characterized by inlet and outlet thermodynamic flow conditions.
Both compressors and turbines rely on performance maps generated using meanline codes developed by a commercial partner. The turbine model features NGVs for back-pressure control by regulating the turbine mass flow rate. Turbine efficiency estimation relies on equilibrium models accounting for humid air condensation during expansion. The RHEX and LHEX models are respectively herringbone fins air-to-air and louvered fins and flat tubes HEXs. These lumped-parameter models feature topology-dependent correlations for heat transfer coefficient and pressure drop estimation, together with the effectiveness-NTU method for heat balance. The humid air and GW mixture fluid models rely on the equations of state provided by the Modelica Standard Library.
The integrated system optimisation aims to minimise both system weight and power consumption by simultaneously optimising HEX geometry and thermodynamic processes at design point. The outcome is a Pareto front of optimal design points for all system components. The optimisation problem involves 17 design variables, including HEX dimensions, fin geometry, and GW mass flow rate. Optimal solutions are constrained by maximum allowable pressure drop and FC inlet temperature values. The optimisation framework follows the methodology proposed in for aircraft ECS optimisation. It leverages the stochastic NSGA-II algorithm and an API linking the Modelica simulation environment with Python. The aircraft operating envelope and CASS requirements are specified by the manufacturer. After selecting an optimal design, off-design analysis is performed to assess system performance across the full operating envelope and finalise CASS configurations trade-offs.

3. Results & Conclusions

The optimisation results indicate that the CASS configuration incorporating both RHEX and LHEX leads to heavier system designs than the configuration with LHEX-only . Although power consumption is also higher in the two-HEX configuration, the increase is limited to approximately 10 kW. To satisfy maximum pressure drop constraints, optimal designs in the two-HEX configuration feature a large RHEX and a compact LHEX. Conversely, in the LHEX-only configuration, the heat exchanger remains compact despite handling the entire thermal load, thanks to the higher thermal capacity of the GW coolant compared to air. However, the LHEX-only arrangement increases the likelihood of moist air condensation within the turbine, as the inlet air is colder in both standard and cold-day off-design conditions, posing challenges for turbine performance and blade erosion. These findings demonstrate the design optimization method validity when applied to the CASS and showcase the system limitations when removing the RHEX.

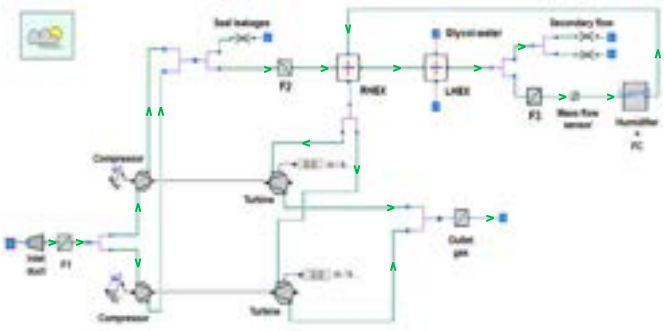


Figure 1. *Modelica model of the Cathode Air Supply System.*

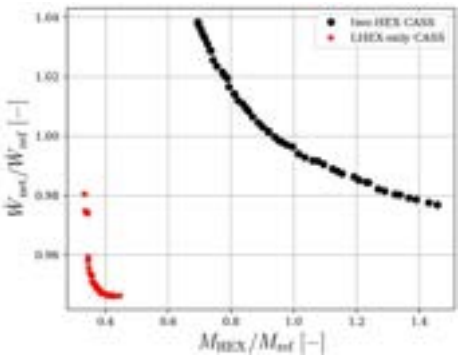


Figure 2. *Normalised Pareto front of the Cathode Air Supply System optimization for two-HEX and LHEX-only configuration.*

High-Temperature PEM Fuel Cells for Hydrogen Aviation: Technology Evolution and Integration Perspectives

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1. Introduction / Objectives

High temperature polymer electrolyte fuel cells (HT-PEFCs, ~120-200˚C) are promising candidates for future hydrogen-powered aircraft due to their potential to simplify thermal and water management at system level. Compared to low-temperature (LT-)PEFCs (~60-90˚C), their elevated operating temperature enables more efficient heat rejection, potentially reducing cooling system size, mass and aerodynamic drag, while operating under anhydrous conditions eliminates the need for external humidification. Despite these advantages, limitations related to power density, durability and technological maturity still hinder large-scale aviation deployment. This work evaluates the aviation relevance and technological evolution of HT-PEFC systems through an analysis of performance trends and key enabling technologies over the last decade, with emphasis on their implications for aircraft integration. Furthermore, the study identifies major technological bottlenecks and proposes a preliminary roadmap for the deployment of HT-PEFC technology in future aviation applications.

2. Methodology

This work applies a multi-scale technology assessment and benchmarking approach to evaluate the suitability of HT-PEFCs for future aviation applications. First, the study compares HT-PEFC with state-of-the-art LT-PEFC technologies against key aircraft performance targets for 2030, including electrode power density, stack and system gravimetric power density, durability and thermal management requirements. Corresponding performance indicators are normalized with respect to the aviation targets and analyzed using radar-chart visualization.

Subsequently, the study investigates the technological evolution of HT-PEFCs at cell, stack

and system level. At cell level, a comprehensive review of approximately 140 relevant studies published over the last two decades was conducted to identify key developments contributing to performance and durability improvements, with particular focus on membrane electrode assembly evolution and phosphoric acid retention strategies, due to their strong impact on HT-PEFC performance and durability. Furthermore, additional degradation and operational challenges under aeronautical conditions are also assessed. Namely, long-term steady state operation, dynamic load variations, and thermal cycling. At stack level, the analysis investigates key strategies to reduce stack mass and facilitate aircraft integration through advanced stacking approaches. At system level, this work evaluates thermal management system mass across different studies, power classes and aircraft integration configurations relevant to MW-scale propulsion systems. Particular emphasis is placed on identifying key trade-offs, enabling technologies and breakthrough concepts contributing to system-level mass reduction and improved integration potential. Based on the identified technology gaps and maturity limitations, the current readiness of HT-PEFC technology for aviation applications is assessed and future development pathways toward aerospace deployment are proposed.

3. Results / Conclusions

The comparative assessment highlights significant differences between LT-PEFC and HT-PEFC technologies for MW-scale aviation applications. Figure 1 shows that although LT-PEFCs continue to outperform HT-PEFCs at cell and stack level power density, recent advances in membrane electrode assemblies and durability strategies have progressively reduced the performance gap. Furthermore, data indicate potential system-level benefits for HT-PEFC despite their currently lower stack performance. This reflects a trade-off between lower stack-specific power density and the potential for reduced thermal management and balance-of-plant mass enabled by elevated operating temperatures, with additional gains expected from future stack-level improvements. The increased temperature gradient facilitates effective heat rejection and advanced cooling integration. Namely, turbo-air, nanofluid and phase-change cooling concepts were identified as promising pathways toward larger aircraft classes. Hence, the resulting technological progress positions HT-PEFCs as a strong candidate for MW-scale aviation propulsion, while highlighting the critical development priorities for further improvement in durability and power density.

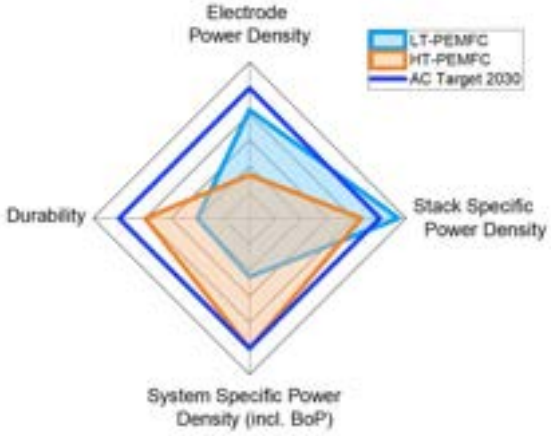


Figure 1. *Spider diagram comparing key characteristics of LT-PEFC (light blue) and HT-PEFC (orange) based on data from Ref. , normalized with respect to projected 2030 aircraft performance targets .*

Dynamic Analysis of Double-helical Planetary Gearboxes using Multi-Body Simulation

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1. Introduction / Objectives

The reduction ratio with the planetary gearbox and the slower rotation of the fan make modern civil turbofan engines more efficient and quieter. However, as the gearboxes have to deliver very high performance, it is essential that they also meet the highest quality standards. This is ensured, among other things, by correct assembly and the investigation of assembly tolerance deviations on the engine operating behaviour. In the context of this work, it is examined how unfavourable tolerance combinations lead to poorer operating behaviour as well as to a shortened service life. Unfavourable tolerance combinations can have a negative impact on operating behaviour and lead to increased wear. In this project, the assembly and manufacturing deviations that affect the relative position of the ring gears are investigated with the help of vibration analysis and multi-body simulation applied to gearbox test bench data. This research project is being conducted in collaboration with TU Wien (Machine Elements and Transmissions for Aviation) and Aerospace Transmission Technologies GmbH.

2. Methodology

In order to be able to assemble double helical planetary gears, the ring gear is often manufactured in two parts shown as in Figure 1 and the two halves are joined together after assembly. To ensure that the two halves are not rotated relative to each other, a methodology is to being developed that uses structure-borne noise and vibration analysis to provide a clear indication of the rotational deviation.
The approach of vibration analysis was chosen for this purpose, as it always considers the entire system and thus also allows other assembly or manufacturing deviations to be detected.
The relative rotation of the two half of the ring gear, has the greatest influence on gear tooth excitation. Radial distortion of the ring gear results in different meshing forces for the left and right sides of the gear pair. This influence is particularly noticeable in the excitation of meshing noises. The focus of consideration here is therefore on the tooth engagement frequency and the sidebands around the tooth engagement frequency.
At planetary gearboxes with evenly distributed planets and sequential engagement there is a shift by the carrier's rotation of the gear meshing frequency. Kang and Kahraman investigated the bahvior of double helical gear pair with staggered angle and showed, that the right-to-left stagger angle influences the behavior of a double-helical gar pair significantly.
In the simulation model, the individual bodies are treated as rigid bodies, since the test bench tests were conducted at low power levels. The focus is on modeling the contact between the double-helical-planet- and ring-gears to simulate the relative-position of the ring gears relative to each other. The gearing is modeled using force elements in the multi-body simulation, thereby also modeling the stiffness, damping and friction of the individual components. The relative ring gear rotation will be introduced as an angular offset between the left and right halves of the ring gear. The calculation is performed for both transient and

steady-state conditions, with the phase shift in the time signal being particularly significant in this contest. In the frequency domain, the sidebands are of particular interest for the analysis.



Figure 1. *Planetary gearbox with the ring gear manufactured in two parts.*

3. Results / Conclusions

Considering the case of a planetary gear with evenly distributed planets and sequential engagement.

Initial investigations show that the position and amplitude of the tooth engagement frequency change as a result of the relative position of the ring gears. Furthermore, the position of the sidebands and their amplitudes also shift. This may be an indicator that the relative position of the ring gears to each other can be detected in a targeted and robust manner using vibration analysis.

The work advances the state of knowledge in the field of operating and vibration behaviour of double helical planetary gearboxes with regard to tolerance deviations due to manufacturing. With this methodology it is possible to test planetary gearboxes with very high performance and with low loads, and still keep the test bench complexity low, compared to a dynamometer where testing is done with full load. This makes it possible to reduce the number of test runs with the complete assembled aircraft engine and, through early detection, cut costs associated with test bench runs and testing.

Preparation and testing of the gearbox, which combines the output power of the GTE and the electric engine to drive the air propeller of a hybrid turbo-electric propulsion

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1. Introduction / Objectives

The article highlights the main stages of preparatory work for ground testing of a demonstrator gearbox that transmits power to the air propeller, obtained by combining the power of a gas turbine and electric engines. This hybrid turbo-electric propulsion (HTEP) is being developed with the aim of reducing the environmental impact of aircraft emissions, in line with the European Green Deal with the goal of ensuring environmental neutrality in the European Union by 2050, as well as one of the Goals of the ACARE Flight Path 2050 programme (Challenge 3. Protecting the environment and energy supply).

2. Methodology

Paper within the EFACA project describes the process of selecting the optimal configuration of a hybrid turbo-electric propulsion (HTEP) for regional aircraft with a capacity of up to 80 passengers and a range of up to 1,000 km.
In order to validate the feasibility of the selected HTEP architecture, a reduced-scale demonstrator has been designed (Fig. 1).

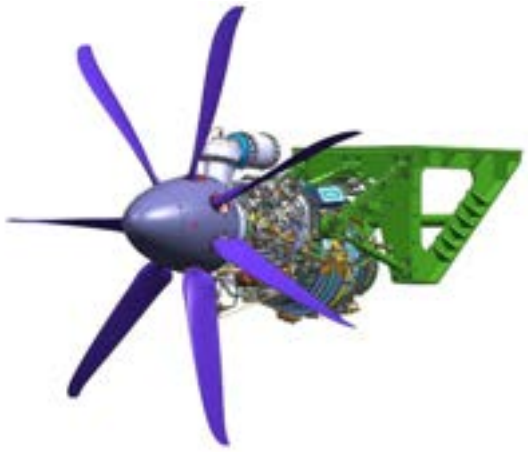


Figure 1. *3-D model of the HTEP demonstrator*

In order to reduce the development time and cost of the demonstrator, a production GTE was selected. This accounted for the engine parameters required by the EFACA project, as well as the cost of manufacturing additional HTEP components and modifying the test rig. The HTEP demonstrator is intended for investigating the performance of propulsion systems in underground test conditions. This includes measuring torque and transient torque response, power output, air propeller thrust, vibration levels, noise, emissions and stresses in the air propeller shaft at all power settings and drive engagement modes. Test cases will include the engagement and disengagement of individual drive units, as well as emergency scenarios.

3. Results / Conclusions

The planned test campaign will provide performance characteristics of the HTEP demonstrator, enabling further development of the propulsion system to be refined, including preparation for subsequent flight-testing.
In particular, the efficiency of the HTEP components is to be determined, including the gas turbine engine (GTE) and electric engine (EE). The interaction between the GTE, EE and propulsion control systems must also be evaluated under steady state and transient

operating conditions.
Additionally, vibration activity, thermal state, and overall operability of the HTEP components will be assessed.

Design and Validation of a Battery Module for High-Power Aeronautical Applications

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1. Introduction

The development of airworthy batteries is still an active area of development with no fully EASA certified solutions yet. Current battery modules and small packs are available mainly for CS-23 Level 1-2 aircraft with energy density and power capabilities limited by the use of COTS cells. Next generation more- and hybrid-electric CS-25 and CS-23 Level 4 aircraft require safety compliant, high-performance and compact battery storage systems. This paper presents the development and testing of a high-performance 1 kWh battery module prototype developed within the Clean Aviation NEWBORN (GA 101101967). The ambition was to consider the stringent safety implications from EASA MOC 3 SC-VTOL and DO 311-A regulations while optimizing the battery module for the competing targets of cell-to-cell thermal runaway non-propagation, high power requirements, and adaptive cell tensioning.

2. Methodology

The development first focused on cell characterization and safety testing at cell and cell stack level to develop thermal runaway mitigation measures tailored to the high-performance pouch cells. Cell characterization tests included rate capability, Hybrid Pulse Power Characterization (HPPC), and cycling life also considering the foreseen flight profile with high C-rate charge and discharge phases. Cell thermal stability and thermal runaway propagation at cell stack level were assessed. Thermal runaway was initiated by overheating or overcharging of a trigger cell and focused on the assessment of the cell-to-cell thermal insulation considering classical and advanced thermal materials, including fiber-reinforced aerogel. The design of the battery module (as shown in Figure 1), in 16s2p configuration providing a nominal output voltage of 55 V, followed DO-311A and focused on the development of the thermal manage ent syst oning mechanism.

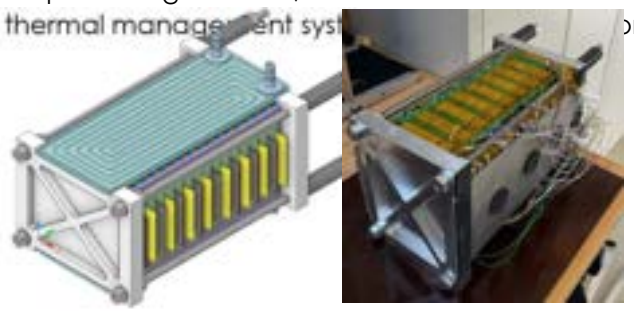


Figure 1. *Battery module cell stack: CAD model (left) and assembled prototype (right).*

Multiple cooling methods (air, immersion, indirect liquid) were evaluated with ANSYS Fluent coupled with an Equivalent Circuit Model for the cell's electrical-thermal performance. Indirect liquid cooling with cold plates on the top and bottom of the cell stack was selected,

with aluminum sheets thermally connecting to the cells. Based on cell safety testing results, cell-to-cell and module thermal insulation and mechanical protection was established by a stack of silicate wool and mica sheet.
Several options to provide the minimum required cell operating pressure of 300 kPa, such as fixed-distance compression with foam materials, passive spring-based system, and an active system using stepper motors were evaluated. The spring-based solution coupled with compliant material for the accommodation of cell breathing was selected due to its simplicity and effectiveness.
The rate capability, HPPC and performance under the realistic power profile of the module prototype were evaluated. Individual cell voltage, temperature at multiple module positions and stack pressure were measured during testing.

3. Results / Conclusions

The prototype battery module confirmed safe operation across the full flight profile with a maximum cell temperature below 55 °C and a cell-to-cell gradient under 5 °C with the cell stack pressure remaining in the target range. The cell-to-cell insulation demonstrated effective protection against thermal runaway propagation. The cell stack showed a moderate weight packaging efficiency of 41%, primarily due to the suboptimal cell format and tensioning mechanism weight. An optimized cell stack design could improve the weight packaging efficiency to above 70%.
These findings highlight the importance of cell selection in the early stage of module development. The specific choice of cell chemistry and format introduces cascading effects across safety and thermal management requirements, and achievable mass and volume. This work establishes a foundation for future iterations aiming to balance high performance with the strict weight and volume requirements of next generation more- and hybrid-electric aircraft while ensuring safety.

Assessment of floating bus voltage on a cycle-integrated SOFC gas turbine hybrid

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1. Introduction / Objectives

In the EU-funded HYLENA (HYdrogen eLectrical Engine Novel Architecture) project , the synergistic integration of novel hydrogen Solid Oxide Fuel Cells (SOFC) propulsion technologies is explored. Hydrogen hybrid-electric propulsion systems integrating SOFC and electrical motor (eMotor) with gas turbines (GT) offer a promising pathway toward high-efficiency and low-emission aircraft propulsion . The HYLENA concept utilizes an SOFC supplied eMotor connected to the low-pressure spool of a turboprop gas turbine for a regional aircraft application, comparable to ATR72. Hence, the electrical architecture performs a critical role in power management between the electrochemical and turbomachinery systems. Conventionally, electrical propulsion architectures employ a fixed bus voltage to allow compatibility of downstream electrical components, however, every component within the electrical propulsion system increases complexity, mass and efficiency losses. This paper investigates whether a simplified SOFC driven floating (no DC/DC converter) electrical architecture would represent a feasible alternative to a fixed voltage architecture (with DC/DC converter).

2. Methodology

The removal of electrical components could provide an overall efficiency-chain gain and mass and complexity reduction, as the bus operating voltage is solely driven by the SOFC output. Then, this study performs a trade-off analysis between the potential efficiency losses of a floating voltage architecture and the reduction in component sizing compared to fixed-voltage systems. The two floating and fixed voltage electrical architectures to be studied are shown below in Figure 1.

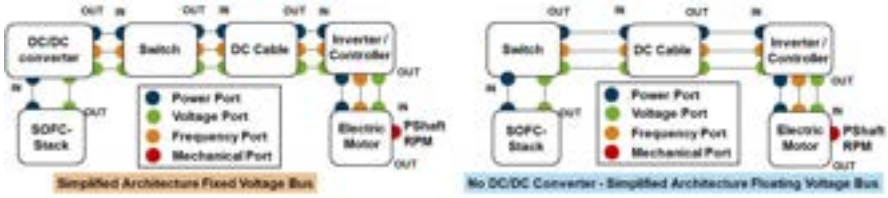


Figure 1. *Two Simplified Electrical Architectures under investigation: fixed and floating voltage*

The envisaged general iterative workflow is shown in Figure 2; it shows a map-based methodology for the electric system to capture component-specific operating points. The working principles of the steady-state 0D-approach fuel cell modelling used in HYLENA will not be part of the focus of the paper, but the effects will be captured on the electrical system for given power splits (ratio between GT's and eMotor's shaft power). A steady-state modelling approach was developed to capture the interaction between the SOFC temperature-pressure and voltage-current characteristics. The approach employed the Nernst equation and Area-Specific Resistance (ASR), and obtained the electric machine performance under varying operating conditions and power settings. Consequently, the SOFC power output (current and voltage) varies, affecting electrical components' operating point and efficiencies. The modelling approach is built into Bauhaus Luftfahrt's in-house developed multidisciplinary design and performance synthesis framework APSS ("Aircraft Propulsion System Simulation ") . This framework integrates electrochemical SOFC performance models, electric drive systems, and gas turbine cycle simulation.

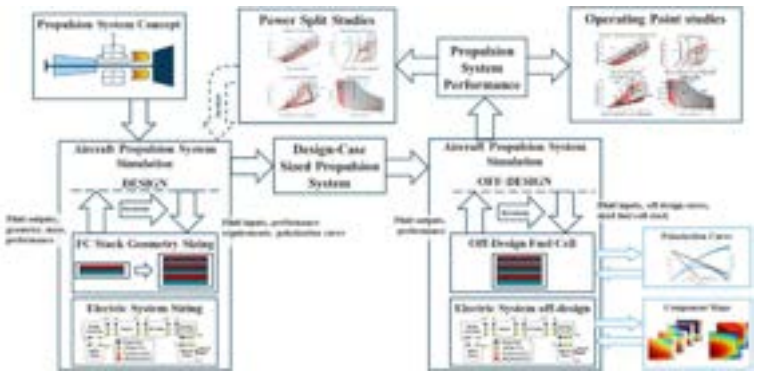


Figure 2. *Schematic of the general workflow methodology (adapted from)*

3. Results / Conclusions

The effects of the SOFC bus voltage (at off-design points) and the chosen design point

voltage will be shown allowable operating envelope of the eMotor in off-design conditions. Furthermore, it could limit the maximum allowable off-design power split or will show a different eMotor design point to meet the power split requirements. This is due to SOFC supplied voltage and current output does not match the required voltage/current requirements for the operating point necessitating redesign of the electrical system.

Potential to increase roll authority using differential thrust in a distributed electric propulsion aircraft under actuator and propulsion failure

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1. Introduction / Objectives

In view of increasing CO_2 emissions from air traffic, attention is turning to electric propulsion systems. Distributed Electric Propulsion (DEP) enables new aircraft configurations to be realised by integrating the propulsion system into the aircraft's airframe, interacting in a more efficient way with aircraft systems, and taking advantage of aero-propulsive effects. These effects lead to increased propulsive efficiency and improved low-speed performance, as well as new design possibilities for aircraft control.
Previous investigations have already been shown the potential of using electric propulsion for flight control to improve yaw performance and low speed handling qualities. This work demonstrates the impact of differential thrust on the effectiveness of the ailerons and how this subsequently influences roll performance. The effects of different thrust configurations and flight phases are analysed. Malfunctions are integrated, and the behaviour of the roll authority is demonstrated by varying the local airflow on the aileron.

2. Methodology

The starting point for the investigations is a CS-23 aircraft with a classic wing fuselage configuration as a low-wing aircraft with a T-tail seen in figure 1. The propulsion technology used is distributed electric propulsion. The aircraft model is provided in xml-based data format, including geometry, mass distribution, and control surfaces. A multiple lift line method is used to determine the aerodynamic data, reproducing the corresponding lift and drag coefficients. Propeller-induced velocity fields are also calculated and added to the lifting line method, enabling the aero-propulsive effects to be accurately mapped. Increments in the force and moment coefficients depending on flap and aileron deflection are also be calculated. As the multiple lift line method only determines lift and induced drag, the force and moment coefficients resulting from the thrust and pressure drag increase due to rudder deflections must be determined separately in order to carry out the flight mechanics evaluation. Out of this data a six-degree-of-freedom (6-DOF) model is derived in MATLAB/Simulink, which is used to analyses the handling qualities (roll performance). After the model has been trimmed to each individual thrust constellation, the model is loaded with control inputs and the reaction is recorded.
In the first part, the effectiveness of the ailerons is determined as a function of thrust. The thrust is symmetrically and varied between 25% and 100%. Three flight phases are analysed: takeoff, climb and cruise.
In the second part, a malfunction of the aileron is simulated: One aileron is blocked in the deflected state. The thrust of the engines in front of the functioning aileron is increased, while the thrust in front of the defective aileron is reduced. This differential thrust should be

reducing the effectiveness of the aileron, thereby reducing the influence of the malfunction, while increasing it on the other aileron. The remaining engines are trimmed so that the resulting yaw moment is close to zero (figure 2). Different levels of thrust are applied, focusing on the flight phases which showed the greatest influence on aileron effectiveness resulting from the first part.



Figure 1. *D-LIGHT Aircraft (DLR)*



Figure 2. *Thrust allocation with malfunctioning right aileron stuck in full negative position*

3. Results / Conclusions

As expected, the results in the first part qualitatively show that aileron effectiveness can be increased with higher thrust levels depending on airspeed. At low airspeed like in takeoff and climb the impact is higher, while at higher speeds the prop induced flow has no significant influence on the aileron effectiveness. In practice, the ailerons are sized according to the slow flight phase, e.g. the 2nd segment climb, as the control surface effectiveness is quite low. Therefore, in combination with propeller flow the sizing point of the control surfaces can be shifted.

In the second part, the results show that compensation of the malfunction is possible, but the handling quality is limited. The superposition of the roll moment from the propeller wing interaction from differential thrust, with those from the change in aileron effectiveness, increases or decreases the roll rate depending on the roll direction.

EProNS – An Electric Propulsion Network Simulation Module for GTlab

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1. Introduction / Objectives

The electrification of aircraft propulsion systems poses significant challenges for power simulation and requires an integrated analysis of thermodynamic and electrical subsystems. Conventional gas turbine simulation environments lack native capabilities for modelling complex electrical networks with bidirectional power flow. This study presents a methodology for embedding electrical network simulation into the established gas turbine laboratory

framework GTlab , which enables the performance evaluation of both all-electric and hybrid-electric as well as "more electric" powertrain architectures. The proposed approach supports arbitrary network topologies as well as bidirectional load flow analysis and considers functional dependencies through component performance maps. The approach enables a direct coupling between performance calculations for gas turbines and the analysis of electric networks, allowing a comprehensive assessment of hybrid-electric powertrain architectures. This integrated framework closes a critical gap in current simulation capabilities and supports the development and optimisation of next generation propulsion systems.

2. Methodology

The Electrical Propulsion Network Simulation (EProNS) module extends the GTlab framework to enable the analysis of electric propulsion systems. It supports all-electric, hybrid-electric and more-electric powertrain architectures by coupling with the existing performance calculation module. Therefore, a stand-alone power flow calculation method was used, which is based on a load flow analysis for hybrid AC-DC systems, as described and validated in detail by Bahrs *et al.* .

The methodology adapts classical load flow analysis to accommodate for mixed AC-DC architectures characteristic of electrified aircraft propulsion. The bus-based modeling determines the electrical network parameters through power balancing using Kirchhoff's and Ohm's laws. Therein, the method was extended with converter models which enable voltage type and level changes between subsystems while maintaining bidirectional power flow. Three converter types are implemented: AC-DC converters for inversion and rectification with direction-dependent efficiencies, DC-DC converters for voltage conversion with boost and buck modes and AC-AC converters that take voltage ratio and phase shift into account. Functional dependencies of system parameters - such as the efficiency of converters, which changes with the current flow or voltage - are taken into account by performance maps and enable coupled component design through an inner iteration loop. An exemplary electric powertrain network set up in the EProNS module is shown in Figure 1.

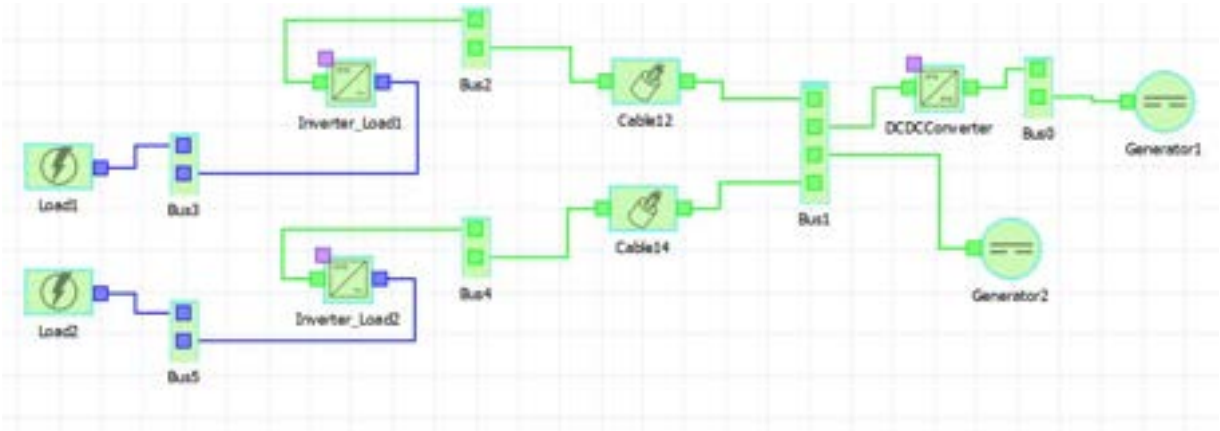


Figure 1. *Exemplary electric network set up in GTlab*

The software architecture decouples the underlying model, consisting of equation system and solver, from the graphical user interface allowing for a stand-alone batch mode of the

EProNS module. Nevertheless, a user interface was developed with a dedicated data model representing electrical components including converters, buses, cables, generators, and loads, with AC and DC ports enabling network configuration. An interface layer translates graphical configurations into the computational format required by the solver, enabling bidirectional data exchange and supporting design as well as off-design calculations.

3. Results / Conclusions

The developed EProNS module enables comprehensive simulation of electrified propulsion systems within the established GTlab framework. With the validated load flow methodology detailed in Bahrs *et al.* , accurate performance analysis of electric networks can be carried out. Therein, the implemented converter models assure voltage conversions in hybrid AC-DC architectures, while the integration of functional dependencies through power maps enables coupled component design and power flow analysis.
The developed tool facilitates the performance evaluation of hybrid electric propulsion systems under realistic operating conditions, thereby closing a critical gap in current simulation capabilities. Through close integration with the existing modules for estimating gas turbine performance, the evaluation of both full- and hybrid-electric propulsion system configurations are possible. This advancement supports the ongoing development of hybrid-electric aircraft by providing a unified simulation framework for multidisciplinary analyses.

Aviation's CO2 and non-CO2 emission. Assessing measuring, predicting, and mitigating impact

Chaired by:
Mr. Georgios Bampanis (European Climate, Infrastructure and Environment Executive Agency - CINEA)

The UNIC Project: Objectives, Methodology, and Current Progress

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1. Introduction / Objectives

Aviation contributes approximately 3–4 % of the total anthropogenic radiative forcing in Earth's atmosphere. Up to two-thirds of that contribution is estimated to originate from emissions other than carbon dioxide, also known as non-CO_2 emissions, such as nitrogen oxides NO_x, water vapor H_2O, and particulate matter (PM). Some non-CO_2 emissions play a key role in the formation of both persistent condensation trails (contrails) and contrail-induced cirrus clouds, which are currently thought to contribute the largest share of aviation's non-CO_2 impact on climate . Despite the significance, the exact mechanisms through which non-CO_2 emissions exert this impact still exhibit significant uncertainties. To reduce these uncertainties and advance toward a more complete understanding of aviation climate impact an international effort is underway. The UNIC (Understanding the Non-CO_2 Impacts of De-Carbonised Aviation) Horizon-Europe project brings together innovative in-flight and ground-based emissions measurement methods, advanced lab-scale experiments, and cutting-edge modelling to advance the scientific understanding of real-world emissions from aircraft at cruise altitude. The project investigates the role these emissions play in contrail and contrail-cloud formation, as well as aerosol-cloud interactions.

2. Methodology

To achieve its objectives, UNIC deploys a multidisciplinary approach structured around three main pillars: advanced experimental measurements, high-fidelity modelling, and impact assessment.

The experimental methodology includes the development and validation of a novel airborne instrument designed to measure emissions directly at the engine exhaust. This system will be tested in a demonstration flight campaign with the National Research Council (NRC) Falcon-20 research aircraft in tandem with laboratory studies investigating the fundamental interactions between lubricating oil vapours and combustion emissions. A low-temperature oxidation flow reactor is being developed to replicate and study the chemical aging that occurs during cruise altitudes within a controlled laboratory environment. Finally, the project includes a series of full-scale engine tests that will go beyond standard certification measurements, targeting specifically volatile particulate matter (vPM), electrical charge impact on emissions, and contributions to emissions from the oil venting system. These experimental data feed directly into the modelling work package. First, microphysical models will be used to simulate early-stage particle formation. Then, these models will be integrated into a CFD contrail formation and plume dynamics model to include the role of vPM, electrical charge, and oil vapours on contrail formation. At the regional and global scales, the project integrates these outputs into aerosol-cloud interaction and global climate models.

Beyond the scientific outputs, a dedicated work package is established to synthesize the data generated across the technical work packages into comprehensive policy briefings and white papers. By doing so, UNIC will provide aviation stakeholders, European regulatory bodies, and policymakers with the quantified evidence needed to design future measures.

3. Results / Conclusions

As the UNIC project is currently in its first stage, this presentation will focus on a description of the project's roadmap and its current implementation progress. Updates on the development phase of the novel airborne instrumentation will be presented. Furthermore, the talk will highlight preliminary results and initial insights from the ongoing laboratory studies regarding oil vapor interactions and flow reactor characterization.

Constraining the impact of volatile particulate matter on contrail cirrus forcing estimates – an output of the A4Climate project

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1. Introduction / Objectives

Aviation is responsible for 3 – 4 % of global anthropogenic climate impact[1], driven by both CO_2 and non-CO_2 contributions. The largest of these non-CO_2 drivers is contrails and contrail cirrus, which are ice clouds that form behind cruising aircraft. Contrail cirrus is estimated to have a net warming impact comparable to that of accumulated CO_2 emissions from aviation since its inception. The A4Climate is a European research project focused on contrails. This project draws on the expertise of over 15 academic institutions and industry partners, with work spanning fundamental laboratory measurements, ground and cruise field measurements, process modelling and a climate-optimized flight trial using over 400 commercial flights. As part of this project, the nature of volatile particulate matter (vPM) emissions from aircraft engines has been investigated, as a potential source of contrail ice crystals. This research has been addressed through recent field measurements, laboratory measurements and model simulations.

2. Methodology

Here, we present a recent output from this project: an updated global contrail simulation, which has been performed with the inclusion of volatile particulate matter (vPM). Hitherto, models have assumed that contrails form predominantly from non-volatile particulate matter (nvPM, soot), however recent cruise measurements indicate that for engines with reduced nvPM emissions (lean-burn)[2] or high fuel sulphur content (FSC)[3], vPM can meaningfully contribute towards contrail ice crystal formation. Therefore, overlooking its involvement is understood to result in an underestimate of the global impact of contrail cirrus. To explore the role of vPM in contrail formation, we integrate a microphysical framework[4] within the contrail cirrus prediction model (CoCiP). Using this framework, we can estimate the enhancement in apparent contrail ice crystal emission indices (EI_{ice}), which derive from the activation of vPM into water droplets and subsequent ice nucleation to form contrail ice crystals. Previous simulations show that this enhancement is highly sensitive to the initialized vPM properties, including their size and hygroscopicity (composition). To that end, we constrain these properties using outputs from two recent flight campaigns, which estimate EI_{ice} for engines with reduced nvPM emissions[2]. Using these properties, we provide an updated estimate for the 2019 contrail net radiative forcing (RF), exploring the impacts of lubrication oil emissions and FSC. Moreover, we also investigate the potential benefits associated with fleetwide adoption of 100% sustainable aviation fuel, low-sulphur jet A-1 and adoption of lean-burn engines.

3. Results / Conclusions

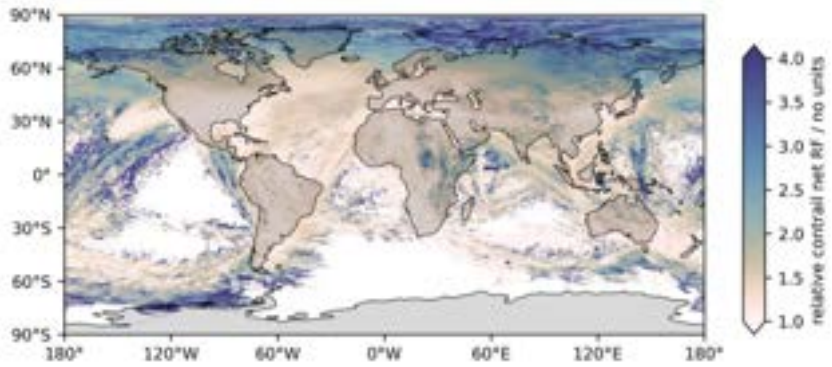


Figure 1. *Relative increase in the contrail net radiative forcing (RF) after accounting for volatile particulate matter contributions.*

In summary, we find that the inclusion of vPM in our 2019 global contrail simulations leads to a relative increase in net RF by +47 [22, 68] %, to 75 [62, 86] mWm^{-2}. This enhancement is driven by a relative increase in average AEI_{ice} for both conventional rich-burn engines and lean-burn engines. Additionally, we find that fuel-based mitigation strategies, including fleetwide adoption of low-sulphur Jet A-1 or 100% SAF result in a reduction in global net RF estimates by 25% and 35%, respectively. Fleetwide adoption of lean-burn engines is also shown to reduce global net RF, with final estimates showing high sensitivity to the assumed vPM properties. Ultimately, these findings underline the importance of increased efforts to understand the nature of vPM emissions from aircraft engines, which is addressed by current research under the A4Climate project.

Environmental impact of a hydrogen-optimised multi-fuel propulsion system

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1. Introduction

Air traffic growth inevitably increases aviation's emissions, hence aggravating aviation's environmental impact locally and globally. Furthermore, the design philosophy of aircraft engines imposes trade-offs between local and global emissions, which require a technological breakthrough. The Horizon Europe project HOPE focuses on developing a multi-fuel propulsion system to minimise the environmental impact of future aviation . The aircraft system features novel multi-fuel ultra-high bypass ratio (UHBR) turbofan engines, a fuel cell-based auxiliary propulsion and power unit (FC-APPU) driving an aft boundary layer ingestion (BLI) propulsor for short- to medium-range flights (A320-like aircraft capacity). In this study, we will present preliminary results on the environmental effects of this novel propulsion system and implications for the future development of the HOPE aircraft to mitigate its overall environmental impact.

2. Methodology

To investigate the environmental impact of HOPE technologies, a holistic approach is considered both at the local and global levels. The main aim is to understand the changes in the environmental impact between the HOPE propulsion concept and its reference (a future geared turbofan configuration with an entry-into-service of 2035 for an A320-like mission).
In the first step, we developed various technological scenarios to assess the fleet development potential until 2070, with and without the introduction of the HOPE aircraft . The modelling minimises the fleet's energy consumption while considering multiple factors, including travel demand, the sustainable aviation fuels mandate and the fuel price of alternative fuels. The outcome serves as the basis for the environmental impact assessment.
For local air quality effects, we developed a systematic airport selection methodology to identify the most representative airports where short- to medium-range flights operate frequently. Accordingly, the effects of aviation NO_x emissions on the atmospheric NO_x concentrations and the effects of non-volatile particulate matter (nvPM) are simulated using the state-of-the-art LASPORT model . The analysis is performed for the reference and HOPE aircraft configurations, allowing us to evaluate the air-quality impact of the multi-fuel HOPE aircraft.
Furthermore, a scenario-based approach is used to assess the climate impact of the multi-fuel HOPE aircraft system relative to its reference case. The temporal evolution of radiative forcing and temperature response can then be calculated using the OpenAirClim model . For the climate impact, the effects of CO_2, NO_x, H_2O, and contrails are included.

3. Results and summary

In this section, we show example results of the air quality and climate impact study for the HOPE reference aircraft. Figure 1 shows an example result of the simulated NO_x concentration at the Madrid airport due to NO_x emissions from the HOPE reference case, based on 707,726 aircraft movements in 2070. Similar results will be shown for the multi-fuel HOPE aircraft in the future to further evaluate the local air-quality impact of the HOPE technology. Figure 2 demonstrates the temporal evolution of the temperature response, accounting for the full set of effects from CO_2, NO_x, H_2O, and contrails. Ultimately, we aim to understand the trade-offs between local and global effects of the HOPE technologies and how these trade-offs change relative to the reference case.

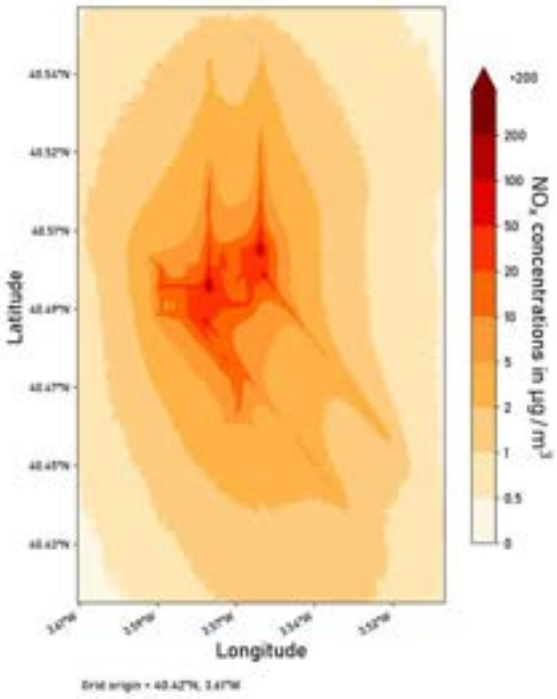


Figure 1. *The first result on the change in NOx concentration at Madrid airport resulting from NOx*

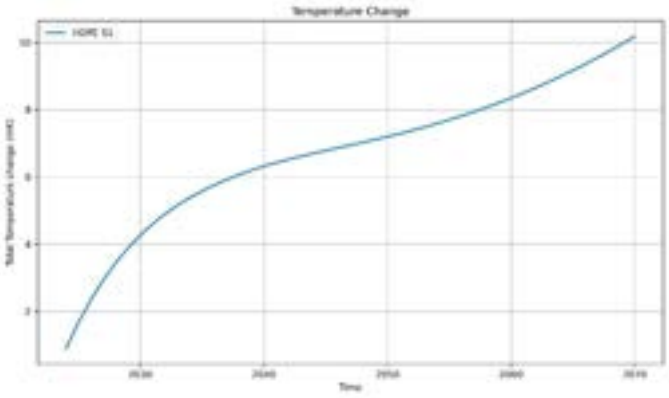


Figure 2. *The first result for the temperature response based on a HOPE scenario (S1) for the reference aircraft propulsion system, considering CO_2, NOx, H_2O, and*

Acknowledgement: The research has received funding from the Horizon Europe research and innovation program under GA n° 101096275 and UKRI Horizon Europe Guarantee n° 10068673.

Latest findings from large passenger aircraft emission measurement campaigns and PACIFIC follow-on activities

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1. Introduction / Objectives

As of today SAF is seen as the biggest enabler to reduce the climate impact from aviation. It not only has the potential to reduce net-CO2 emissions by around 65% , but also to mitigate some of the non-CO2 emissions effects. As shown by Lee et al. in 2021, non-CO2 emissions contributed to 66% of the total effective radiative forcing attributed to cumulative aviation emissions over the period 1940-2018 , but have large uncertainties.

From previous studies it is known that the fuel composition plays an important role for soot emissions as well as for volatile particles formed in the engine plume after mixing with ambient air. Those emissions not only have a direct radiative impact, but also affect contrail properties, can enhance natural cloud formation, and affect local air quality on ground.

2. Methodology

To quantify the impact of fuel composition Airbus conducted in the past years, in collaboration with DLR, engine manufacturers, fuel suppliers and research institutes several ground and flight test campaigns (ECLIF3, VOLCAN, ECLIF-X). In these test campaigns different flight test aircraft from Airbus were, while burning different types of fuel, chased by the DLR Falcon 20 research aircraft.
Although the test campaigns all confirmed the soot and volatile particle reduction potential related to fuel composition , they also left the question open about the relative contribution of the fuel composition, the combustor type/design and the engine cycle (which determines the combustor entry conditions).
To bridge this gap the Horizon Europe project PACIFIC (Particle emissions, Air Quality and Climate Impacts related to Fuel Composition and Engine Cycle) has been launched. It will cover a large set of fuels and test them from lab to full scale. Using advanced measurement and analytical methods will enable the learnings of those experiments to be transferred into simulations of contrails and their climate impact, as well as into an assessment of mitigation measures and potential policy implications.

3. Results / Conclusions

The presentation will show the latest findings from the previous test campaigns, and how PACIFIC addresses the open questions. It will give an overview of the project timeline, PACIFIC's approach for the fuel selection, and some insights into the current status of the project.

ESCAPE: A transportable contrail chamber

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1. Introduction / Objectives

Up to two-thirds of aviation's climate impact is estimated to stem from emissions other than carbon dioxide—referred to as non-CO2 emissions. These include nitrogen oxides (NOx), water vapor (H2O), and particulate matter (PM). A significant portion of these non-CO2 emissions contributes to the formation of condensation trails (contrails) and contrail-induced cirrus clouds. Currently, contrails and the resulting cirrus clouds contribute to the largest share of aviation's non-CO2 climate effects.
For an ice crystal to form, water condenses on an ice nuclei particle (INP). These INPs can either be emitted directly into the atmosphere (primary aerosols, such as soot) or generated

within the atmosphere from volatile molecules that sequentially cluster to form an aerosol particle (secondary aerosols). The quantity, properties, and formation of these primary and secondary aerosol particles are key parameters for understanding the formation, characteristics, and climate impacts of contrails and cirrus. However, the number and physical properties of both primary and secondary aerosols are significantly influenced by the fuels used in aircraft.
This study, conducted as part of the UNIC and PACIFIC projects, explores these issues using various fuels.

2. Methodology

INP properties can be studied using a Continuous Flow Diffusion Chamber (CFDC), such as the Portable Ice Nucleation Chamber II (PINCii) , or an expansion chamber, such as the Portable Ice Nucleation Experiment (PINE) . Within these chambers, INP properties can be investigated at various relative humidity and temperature conditions. However, these ice chambers, widely used for atmospheric studies, have limitations in studying aircraft emissions. They have limitations regarding the humidity of the sample air or the total number of primary aerosol particles entering the chamber. Additionally, they are not designed to study the formation of secondary aerosol particles.
To overcome these challenges, we have developed a new innovative device, ESCAPE: Experimental Simulation of Clouds, Aerosol & Photochemistry Environments. ESCAPE is designed to mimic, as closely as possible, direct contrail formation and new particle formation behind an aircraft engine. It has 3 distinct input flows that resemble atmospheric processes behind an aircraft engine. One heated inlet that carries the exhaust from the engine, one bypass flow, and one flow mimicking the air where the aircraft is flying. Temperature (from -60 to +80 °C) and RH of each flow can be regulated independently. Additionally, Ozone, NOx, and background aerosol can be added to either flow. Within ESCAPE, contrails can form and age. Also, new particle formation can occur. ESCAPE is equipped with an adjustable light source that provides OH radicals and initiates new particle formation in the exhaust plume. ESCAPE has a comprehensive set of instruments to measure the different physical aspects of INP properties and new particle formation. Notably, ESCAPE is equipped with mass spectrometers (PTRMS and CI-Tof-MS), aerosol particle sizer (NAIS, DMPS, OPC), and ice chamber (PINCii).
UNIC and PACIFIC bring together innovative ground-based emissions measurement methods using advanced lab-scale experiments. Within these projects, we are investigating the effect of different fuels, and engines on secondary aerosol formation and ice nucleation properties.

3. Results / Conclusions

ESCAPE has been built and tested in the UNIC project. Within UNIC and PACIFIC, ESCAPE will be deployed in test-rig experiments (with DLR), underwind experiments (with Airbus), and at SAR tech (with ONERA). In this presentation, test results and characterization of ESCAPE will be presented.

Space Robotics – Current and Future Trends in Research and Development

Chaired by:
Mr. Jonas Eisenmenger (DFKI GmbH, Germany)

Overview of AI methods and review of the current state of the art in space applications

Mehmed Yüksel[1], Wiebke Brinkmann[1], Nayari Marie Lessa[1,2], Jonas Eisenmenger[1], Udo Frese[2]
[1] German Research Center for Artificial Intelligence (DFKI), Germany
[2] University of Bremen, Germany

1. Introduction / Objectives

Traditional space technologies rely on predictive algorithms that require complete analytical models of system behavior, an approach that reaches its limits when systems become too complex, unpredictable, or difficult to model.. This limitation becomes particularly critical in the context of long duration space missions, where operational environments are harsh, communication delays are significant, and direct human intervention is constrained.
On the other hand, Artificial Intelligence (AI) provides a methodological and technological framework for processing large scale, high dimensional data, identifying latent dependencies, recognizing patterns, and enabling adaptive decision making and control. By augmenting classical deterministic control architectures with learning based and data driven approaches, AI enhances the capability of space systems to operate autonomously and resiliently in uncertain and dynamic environments.
Building upon a preceding study that examined the gap between AI development and field deployment in planetary analog environments, this work extends to a systems-level perspective. The paper will review AI methodologies across the spectrum of space robotic applications and examine emerging directions in the context of ongoing missions conducted by major institutional and commercial space actors.

2. Methodology

The review is structured around two primary domains of space robotics: orbital systems (including on-orbit servicing, assembly, and manipulation) and planetary systems (including surface and subsurface exploration, in-situ resource utilization, and swarm-based operations). For each domain, the relevant AI methodologies are examined in terms of technical maturity, mission heritage, and integration complexity . This dual-domain structure reflects the fundamentally different operational constraints that govern AI design choices in each context.
Both orbital and planetary robotic systems operate under extreme environmental and operational constraints that fundamentally limit the applicability of classical deterministic control approaches. Common challenges include radiation-induced hardware degradation, communication delays ranging from seconds to hours or more. Surface and subsurface uncertainties, as well as environmental contamination, further affect perception and mobility. Domain-specific constraints include propellant sloshing and orbital eclipse-driven illumination variations in the orbital domain, and in multi-robot planetary configurations, distributed task negotiation, cooperative manoeuvring, and shared knowledge

representation. In scenarios where real-time communication is not feasible, where multiple robots must collaborate autonomously, or where humans and robots execute missions jointly over extended periods without continuous human control, AI must ensure safe and resilient behaviour across time horizons spanning days to months.
AI applications address perception and control under dynamic uncertainty, fault detection and isolation against hardware and software anomalies, and autonomous decision-making under limited or delayed ground communication. A particularly active development area involves AI-enabled rendezvous and docking for non-cooperative targets, where classical model-based approaches are insufficient due to unknown target kinematics, and within the scope of In-Space Servicing, Assembly, and Manufacturing (ISAM) , the adaptive operation of systems reconfigured into states not defined at the time of original design. In the planetary domain, AI methods for terrain classification, path planning under uncertainty, and science-driven sampling prioritization reduce dependence on ground command cycles and enable higher degrees of onboard autonomy.
The review is based on a comprehensive analysis of the literature, selected conference proceedings, and publicly available roadmaps from institutional and commercial space actors.

3. Results / Conclusions

This paper provides a structured overview of AI methodologies applied across orbital and planetary space robotics domains, with particular emphasis on modularity, robustness, resilience, and long-term autonomous operation in harsh extraterrestrial environments. Architectural considerations and emerging technological trends are examined in the context of ongoing and planned missions, as well as the research and development pathways pursued by major space agencies and funding bodies. The discussion concludes that AI has evolved from an experimental capability into an active mission, enabling space robotics technology. However, key challenges, including reliable Sim-to-Real transfer, radiation-tolerant computing architectures, and the certification of autonomous decision-making in safety-critical environments, must be addressed through coordinated interdisciplinary efforts to fully realize the potential of next-generation intelligent space robotic systems.

LunarCobot: Development of Servicing Modules for Multi Robot Operation Scenarios on the Lunar Surface

Mehmed Yüksel[1], Wiebke Brinkmann[1], Nayari Marie Lessa[1,2], Jonas Eisenmenger[1], Udo Frese[2]
[1] German Research Center for Artificial Intelligence (DFKI), Germany
[2] University of Bremen, Germany

1. Introduction / Objectives

LunarCobot is a cooperative research project between the German Research Center for Artificial Intelligence (DFKI), the University of Bremen and the University of Stuttgart, which investigates technology development for multi-robot operation on the lunar surface. Multi-robot operation mission concepts include heterogenous teams of mobile robots and robotic elements with varying skillsets in order to investigate and realise challenging or complex surface operation scenarios and new exploration tasks. Besides TRL increase and development of robotic key functionalities for such scenarios, the LunarCobot project investigates the assessment and development of modular, relocatable, robotic servicing modules to assist mobile robotic system in operations as sketched in Figure 1. This paper

describes the current activities of the servicing module development in order to investigate the interfaces between two of the robotic key technologies of the LunarCobot project: a new type of Electro-Mechanical-Interfaces (EMI) for lunar surface operation as well as the Nanokhod Microrover System.

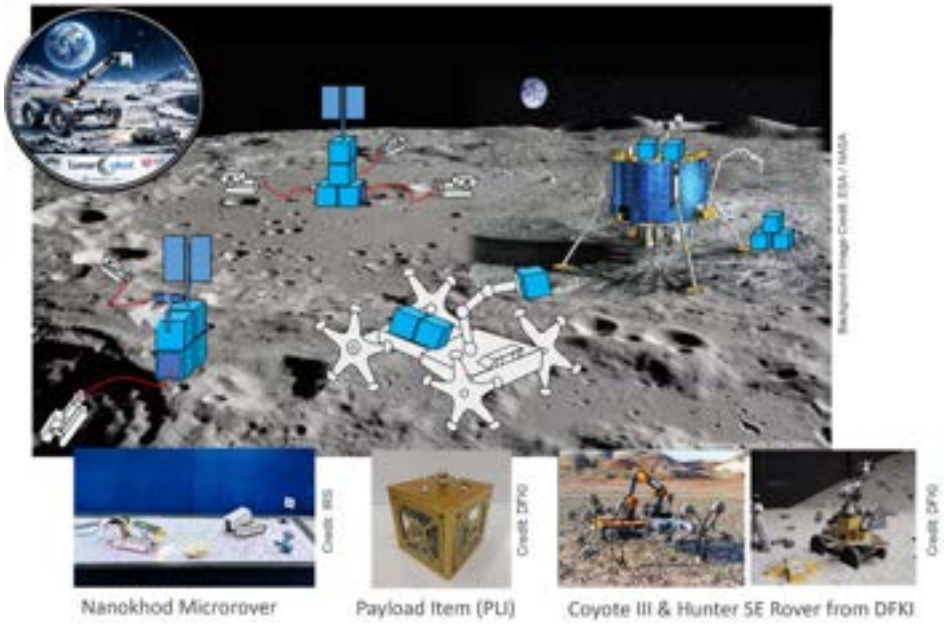


Figure 1. *Sketched concept: LunarCobot – Multi Robot Operation Mission Scenarios using Modular Servicing Modules (blue).*

2. Methodology

The development and realisation of the servicing modules breadboard models presented in this paper were partially included in a higher education program at the University of Stuttgart. The practical project of the course "rover development for exploration tasks" has been successfully implemented at the University since over 9 years and gives participating students the unique opportunity to apply research-oriented learning methods and hands-on project experience by working in state-of-the-art research and development projects. The program applies an adapted ECSS product development and project lifecycle schedule to fit the student-led research and development activities into the 6-month curriculum duration of one semester. Experts from academia, research and industry supervise the student team along the development path and present a reviewer board in the frequent project review milestones. The development activities for development of the servicing modules described in this paper include four major phases: mission, functionalities and requirements definition (1), preliminary concept development (2), detailed design, realisation and testing activities (3) as well as operation in a terrestrial test scenario (4). Applied methods and standards in space engineering follow substantial requirements assessment, concept of operations elaboration, project budgeting (mass, power, data, financial, etc.) and implementation of interdisciplinary engineering work in software development, analytical assessment and load analyses, mechanical CAD design & electrical design.

Key functionalities of the servicing modules for this development phase of LunarCobot were defined into three major categories: the development of the Nanokhod Microrover deployment module (1), a multi-mission power supply module (2), as well as a perception

and operations assistance module (3). All modules are required to be interconnected via electromechanical interfaces to allow a respective connection, power and data exchange in between the modules. A maximum payload module envelope of 30x30x30cm³ as well as mass requirements of 7 kg per module during transport via a larger robotic system are predefined mandatory design requirements. Environmental requirements to be considered for development of the servicing modules include a dust tolerant design due to direct on-surface operation, as well as considerations for operation in a lunar south pole illumination scenario, affecting the assessment of suitable methods for environmental perception.

3. Results / Conclusions

Robotic servicing modules describe an essential building-block in the assessment and realization of modular, reconfigurable mission concepts for further exploration of the lunar surface. This paper presents the ongoing activities in the development of three major types of servicing modules being developed within the LunarCobot project, covering the technical assessment and required functionalities, as well as environmental assessment to be considered for a lunar surface application with specific emphasis on the south pole regions. The paper describes the accomplishment of the first hardware breadboard models being achieved by linking the research work with the space robotics education program at the University of Stuttgart, covering realisation of the modules, onboard software development and assessment of the functionalities in a terrestrial test scenario for different scenarios. The paper summarises the development activities and reflects on the lessons learned to provide valuable contribution for the further technology development within the LunarCobot project.

Multi-Scenario Optimization of PID and Fuzzy Controllers for Astrobee Attitude Control

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1. Introduction / Objectives

Previous research compared the performance of a fuzzy and a Proportional-Integral-Derivative (PID) controller through numerical simulations in the Astrobee platform . The controller parameters were optimized for different tracking error - control effort trade-off scenarios, demonstrating that fuzzy controllers provide promising capabilities compared with PID controllers. However, conventional optimization approaches generally tune the controllers for a single nominal maneuver, resulting in good performance near the design point, but when the controllers are required to execute maneuvers that differ significantly from the nominal case, their performance degrades, an effect that is particularly pronounced in fuzzy controllers.

The primary objective of this study is to introduce a Multi-Objective Particle Swarm Optimization (MOPSO) , in which the controller parameters are optimized over a weighted set of diverse operational maneuvers. The proposed approach aims to develop more robust controllers, capable of satisfying the required operational performance criteria throughout the entire mission profile.

2. Methodology

To address the performance degradation associated with single maneuver tuning, a multi-scenario implementation of the MOPSO algorithm is developed and evaluated. Instead of minimizing the objectives (tracking error and control effort) for a single maneuver, for example, a step maneuver consisting of a 20° rotation about the roll axis, the optimizer evaluates a weighted combination of multiple maneuvers (5°, 20°, 40°, and 90°). For the fuzzy controller, the optimization process parametrically adjusts the shapes of the membership functions, whereas for the PID controller, the proportional, integral, and derivative gains are tuned.

One the controllers are optimized using this multi-scenario approach, their performances are compared with that of controllers obtained through a single-maneuver tuning. A Monte Carlo analysis is conducted to evaluate controller robustness under parametric uncertainties by performing a sweeping analysis over critical variables including maximum available actuator torque, moments of inertia, and a wide range of maneuver angles.

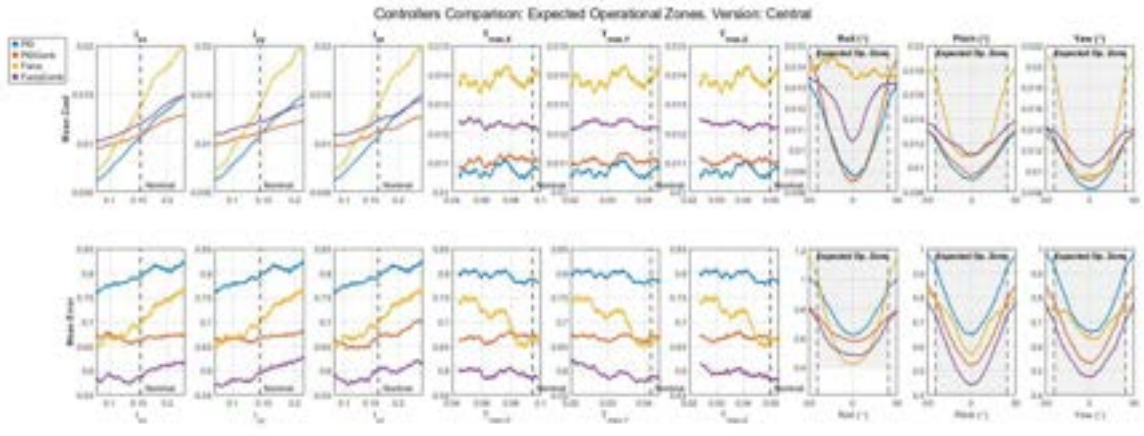


Figure 1. *Mean tracking error and control effort across various maneuvers and parametric uncertainties.*

3. Results / Conclusions

Figure 1 shows some results from Monte Carlo analysis, comparing controllers tuned for a single-maneuver tuning (PID and Fuzzy) with those using the proposed multi-scenario approach (PIDComb and FuzzyComb). The previous controller designs exhibited a substantial sensitivity in error tracking and control effort when subjected to variations in satellite inertia, whereas the sensitivity is significantly reduced with the new multi-scenario tuning. For the remaining sweep parameters, the new methodology reduces the mean tracking error for both the PID and fuzzy controllers, while also reducing the mean control effort for the fuzzy controller, even for larger maneuver angles.

Inertial Parameter Identification for the NASA Astrobee Free-Flyer

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Universidad Politécnica de Madrid, Spain

1. Introduction / Objectives

The NASA Astrobee free-flying robotic platform, operating aboard the International Space Station (ISS), provides a unique testbed for validating advanced spacecraft attitude control algorithms under microgravity conditions . Building on this capability, the FuzzyBuzz experiment was designed to compare different attitude control strategies onboard Astrobee . However, the published nominal parameters may not reflect the actual on-orbit inertial properties of the platform, motivating the need for in-orbit identification. These discrepancies can affect the performance of the attitude controllers, since they have been designed using nominal parameter values.
This work proposes a on-orbit Inertial Parameter Identification for the NASA Astrobee Free-Flyer, to estimate the full symmetric inertia tensor, and provide the accurate parameters required by the attitude controllers.

2. Methodology

For the parameter identification, three methods are used and compared, grounded in established aerospace system identification theory .

1. Equation Error Method (EEM): Euler's equation $\tau = I \cdot d\omega/dt + \omega \times (I \cdot \omega)$, where ω is the angular velocity, τ is the external torque and I is the inertia matrix, is rearranged into the linear regression form $Y \cdot \Theta = \tau$, where $\Theta = [Ixx, Iyy, Izz, Ixy, Ixz, Iyz]^T$ contains all six inertia components and Y is a regressor built from measured angular velocities and angular accelerations, the latter obtained by numerical differentiation of the noisy IMU signal using a smoothing filter .The overdetermined system is solved while verifying that the manoeuvres provide sufficient excitation across all six degrees of freedom.

2. Output Error Method (OEM): This method integrates the dynamic model and minimizes the error between simulated and measured angular velocities using the EEM result as initial guess.

3. Greyest Method: A MathWorks grey-box estimation approach that fits a user-defined dynamic model to measured data, applied here as independent cross-validation.

The three estimators (EEM, OEM, and greyest) are first implemented in simulation, where the true inertia values are known, to confirm that each method can accurately recover them before deployment on the real platform

3. Results / Conclusions

The identification framework is expected to successfully recover all six inertia tensor components from simulated manoeuvre data. The OEM is anticipated to outperform the EEM on all diagonal components, demonstrating the advantage of avoiding noisy signal differentiation. The MathWorks greyest implementation is expected to yield results in close agreement with the OEM, providing independent cross-validation and confirming the reliability of both approaches. Confidence intervals are computed for all estimated inertia components (see Figure 1), confirming that the estimation accuracy meets the requirements for controller deployment.
As the next step, the identified inertia parameters will configure the controllers for the

FuzzyBuzz experiment, where their on-orbit performance will be comparatively assessed under microgravity.

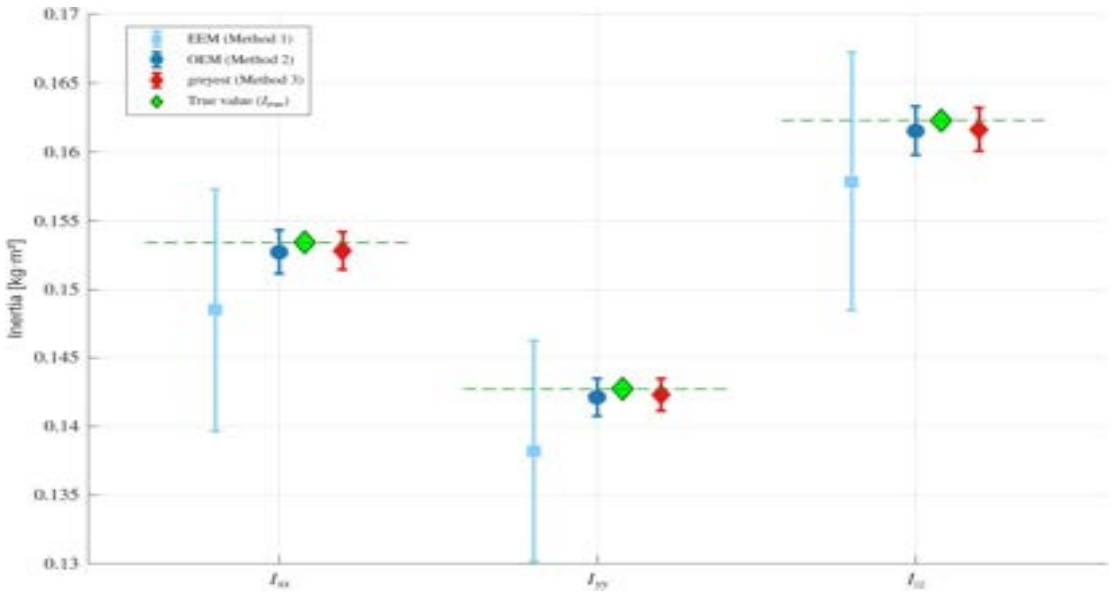


Figure 1. *Estimation results: EEM, OEM and greyest vs true values.*

Reference Scenario and Operational Concept definition for In Space Assembly and Manufacturing Platform

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1. Introduction / Objectives

In the field of spaceflight, innovative approaches are being explored to enhance sustainability and minimize space debris. A modular, maintainable, and reconfigurable orbital architecture is expected to serve as the foundation for future sustainable space solutions, gradually replacing today's highly integrated and small spacecraft. This approach would also facilitate the reuse and recycling of certain satellite components while helping to mitigate the growth of orbital debris. In-orbit manufacturing and integration will enable satellites to incorporate extended functionalities for emerging missions or to replace malfunctioning modules, thereby extending the operational lifetime of satellite systems. Modularity will further support in-orbit assembly, opening new possibilities for constructing structures for diverse future applications, from massive solar energy arrays to lunar gateway platforms.

2. Methodology

STARFAB aims to address a pivotal gap within the Future Space Ecosystem by introducing an innovative concept of an orbital automated warehouse. This facility is designed to serve as a

foundational element and catalyst for a sustainable commercial space operation and service hub, encompassing a wide array of functions, including but not limited to, storage, maintenance, inspection, refueling, testing, recycling, assembly, and manufacturing. This paper presents the operational concept and system specifications for an orbital automated hub centered around a warehouse, along with its associated robotic ecosystem, with particular emphasis on the utilization of servicer spacecraft. Central to the STARFAB automated hub is the Warehouse Unit, which is replenished by cargo spacecraft carrying payloads, satellite modules, raw materials, components for assembly and manufacturing, experimental equipment, and fuel from Earth.

3. Results / Conclusions

The presentation will outline the reference scenarios and Concept of Operations (ConOps) analysis conducted during the STARFAB project, focusing on the consolidation of the Concept of Operations and system requirements. The primary objective is to provide a comprehensive systems-level summary of the end-to-end operation of the STARFAB system across the various mission phases. It will provide an in-depth description of the mission phases, flight operations, operational modes of the system, and contingency scenarios.

ASPERA – Autonomous Spacecraft Pose Estimation with Rendered and Augmented images: A robust VBN for Autonomous Spacecraft GNC in non-cooperative scenarios

N. Andres, H. Fougereau, B. Martinez Borrell, R. Moreau, C. Quivet, J. Ramos Montilla
SII Group, France

1. Introduction / Objectives

Future space missions such as in-orbit servicing, debris removal, and planetary landing increasingly rely on Vision-Based Navigation (VBN) under uncertain and unstructured conditions. However, current VBN approaches suffer from limited robustness when facing non-cooperative targets, variable illumination conditions, sensor noise, optical artefacts, domain gap between synthetic and real imagery . Addressing these limitations is critical to ensure operational safety and autonomy in next-generation missions.
ASPERA aims to develop and validate a robust VBN system for autonomous spacecraft GNC in non-cooperative close-up rendezvous. The proposed solution combines Deep Learning (DL) perception, involving Convolutional Neural Networks (CNN), with classical estimation techniques to significantly improve robustness in feature extraction, tracking, and relative pose estimation. The key innovations include hybrid fusion of deep learning and model-based estimation, robustness to extreme visual variability and domain shifts, adaptive perception pipelines tailored for space conditions, and the integration of AI-based VBN into real-time embedded systems.

2. Methodology

ASPERA proposes a hybrid VBN architecture combining:

- Development and optimisation of AI-based (Deep Neural Networks (CNN-based)) pose estimation models, including feature detection, segmentation, direct pose regression and range estimation. This workstream addresses the domain adaptation

challenge through CycleGAN-Turbo and the exploitation of enhanced synthetic datasets generated in Workstream 2.

- Domain adaptation and randomization strategies to bridge the sim-to-real gap. High-Fidelity Image Simulation and Scene Generation. Development of realistic space image simulation capabilities to reduce the synthetic-to-real gap and improve AI training performance. This workstream also generates updated target spacecraft views throughout the rendezvous sequence based on the relative dynamics computed in Workstream 3.
- Autonomous Navigation, Guidance and Control. Development of the navigation, guidance and control (GNC) subsystem and associated physical simulator for autonomous rendezvous operations. The system exploits pose estimation outputs from Workstream 1 to perform relative navigation and approach manœuvres. Classical estimation techniques (e.g. Kalman filtering, bundle adjustment) for state estimation and consistency.
- Embedded AI optimization for real-time onboard processing. Integration of the perception and GNC algorithms on representative embedded hardware and validation under realistic operational conditions. This workstream assesses the complete closed-loop approach chain, including iterative image generation, onboard processing, system interactions and end-to-end performance evaluation.

The system will be designed to operate in representative mission scenarios, including:

- rendezvous with non-cooperative spacecraft,
- fly-around and motion synchronization,
- planetary landing under uncertain terrain conditions.

3. Results / Conclusions

1 - Fusion of synthetic and pseudo-real datasets reduced the domain gap from ~80% to ~40% on real imagery and fully mitigated the synthetic-to-pseudo-real gap. CycleGAN and enhanced synthetic data were identified as key enablers for domain adaptation.
2 - A Blender-based image generation pipeline was developed to create target-specific datasets from CAD models, enabling robust training and reducing domain-gap-induced performance losses. Further dataset expansion will improve generalization across unseen scenarios, as illustrated in figure 1.

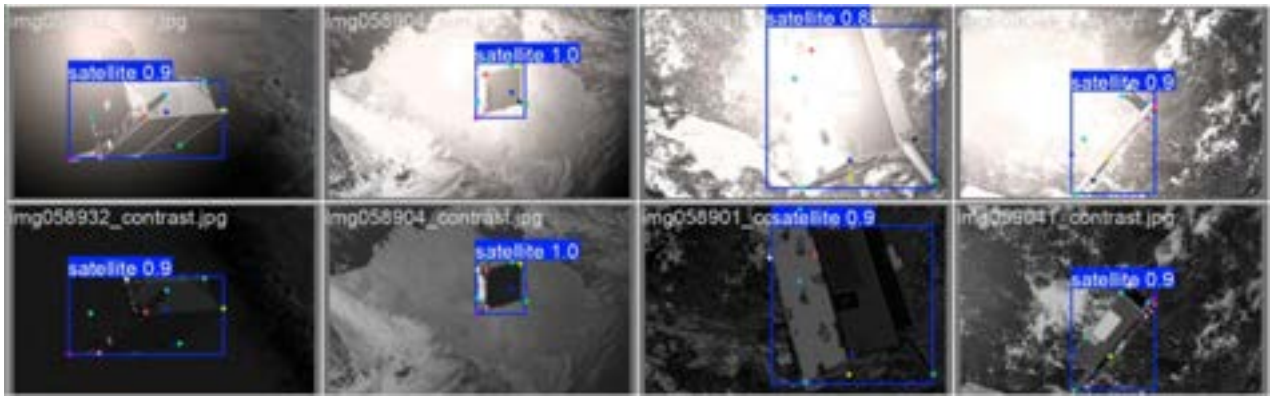


Figure 13: Pose estimation for several noisy parameters

3 - The preferred Heatmap-based Covariance Matching and Mahalanobis Distance approaches demonstrated robust pose estimation and tracking for non-cooperative targets, targeting OKS ≥ 80%, update rates of 10–30 Hz and state-estimation divergence below 2%.

4 - The perception pipeline was successfully deployed on embedded hardware using ONNX and Vitis AI. End-to-end latency was reduced from 150 ms to 55 ms (~18 FPS) while preserving pose estimation accuracy, paving the way for full closed-loop validation..

Sustainable Smart Composites: Cutting-edge Materials and Innovative Manufacturing Processes

Chaired by:
Prof. Liberata Guadagno & Dr. Raffaele Longo (University of Salerno, Italy)

Bridging Recycling Technologies and Material Design: Vitrimers for Sustainable Epoxy Composites

***Liberata Guadagno*[1], *Raffaele Longo*[1], *Marialuigia Raimondo*[1], *Luigi Vertuccio*[2], *Rosamaria Russo*[1]**
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1. Introduction

Existing recycling methods for thermosetting composites have significant drawbacks. Mechanical recycling is the most mature but lacks retention of material value. Thermal recycling allows carbon fiber recovery at significant energy penalties. Chemical recycling aligns best with circular economy principles, through superior material recovery, yet remains constrained by scalability and cost. Increasing attention is being given to recyclable formulations, dynamic covalent networks (vitrimers), and design for recycling approaches. These strategies shift the paradigm from recycling after failure to recycling by design, potentially overcoming the intrinsic limitations of conventional thermosets. Vitrimer-based epoxy composites are gaining increasing attention, displaying mechanical performance comparable to conventional thermosets, while enabling reprocessability, repairability, and improved compatibility with chemical recycling pathways. This category of materials is expected to bridge the gap between high-performance applications and material circularity. This research work explores the possibility of developing recyclable vitrimer composites with the mechanical requirements for load-bearing aeronautical and aerospace applications.

2. Methodology

The epoxy formulations (EP) developed within the present research were obtained by using

GreenPoxy-28 (GP), an epoxy reactive monomer similar to DGEBA (Diglycidyl ether Bisphenol A) with a bio-based carbon content of 28% supplied by Sicomin (Châteauneuf les Martigues, France)(Figure 1a), and the curing agent 2-Aminophenyl disulfide (2-AFD) provided by Sigma-Aldrich (St. Louis, Missouri, US) as vitrimeric hardener (Figure 1b). For the GP, an epoxy equivalent weight (EEW) of 178.9 g mol^{-1} has been considered, and the mixture was prepared using a stoichiometric ratio of epoxy precursor and hardener. Considering the active hydrogens in the 2-AFD chemical formula, 1.000 g of epoxy precursor was used per 0.347 g of 2-AFD. 2-AFD was dissolved in the mixture under magnetic stirring at 100 °C for 10 minutes, obtaining a homogeneous mixture.
The obtained epoxy mixtures were degassed for 1 h at 80 °C and then poured into metallic moulds for a two-step curing cycle: 1 h at 150°C and 2 h at 200°C.
The developed materials were characterized via Differential Scanning Calorimetry (DSC) analyses using a Mettler Toledo DSC 822e purged with nitrogen. Fourier Transform Infrared spectroscopy (FT-IR) was conducted with a Bruker Vertex 70 FTIR-spectrophotometer (Bruker Optics Inc., Billerica, MA, USA) in the range of wavenumber between 4000 and 400 cm^{-1}, with a resolution of 2 cm^{-1} (32 scans collected). Thermogravimetric analyses were performed on the samples using a Mettler Toledo Mettler TC-10 thermobalance.

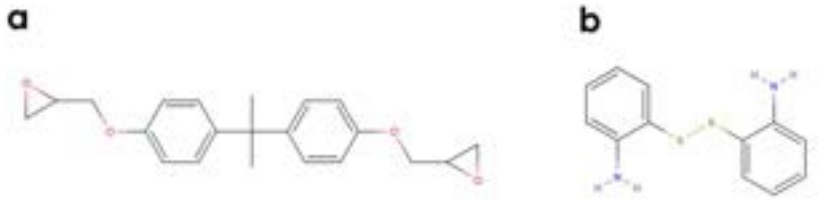


Figure 1. *Chemical structure of epoxy precursor similar to GP (a) and 2-AFD (b)*

Vitrimeric composites were obtained by using EP and reinforcement fiber of interest of the aerospace and aeronautical sector. Dynamic Mechanical Analysis (DMA) was performed to evaluate the thermomechanical performance of the developed epoxy resin.

3. Conclusions

In this research work, fiber-reinforced vitrimeric composites have been successfully developed and characterized. Thermal and kinetic analyses were performed to investigate the curing mechanisms and to confirm the efficient formation of the polymeric network. These composites exhibited outstanding thermal stability, high glass transition temperature (T_g), and an elevated elastic modulus. Due to their high thermomechanical properties combined with intrinsic self-healing properties, these materials turned out to be promising candidates for aeronautical and aerospace applications. Furthermore, 2-AFD was used as a vitrimeric hardener to obtain covalent adaptable networks (CANs), enabling the recycling of the obtained composites. The present research proposes an innovative strategy for the development of load-bearing composites, which addresses the end-of-life challenges associated with the conventional thermosetting materials in aeronautic and aerospace engineering.

Reprocessability by Design: High-Performance Bio-Based Epoxy Vitrimers for Fiber-Reinforced Composites

Liberata Guadagno[1], Francesca Aliberti[1], Luigi Vertuccio[2], Marialuigia Raimondo[1], Roberto Pantani[1], Raffaele Longo[1]
[1]*University of Salerno, Italy*
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1. Introduction

Lightweight fiber-reinforced composites are widely used in the transportation and aerospace industries for their outstanding mechanical properties. These materials are predominantly based on thermosetting polymer matrices, which, despite their excellent structural performance, are not effectively recyclable, posing significant sustainability challenges. Vitrimers have recently emerged as a promising alternative, combining the mechanical robustness of thermosets with the reprocessability of thermoplastics through dynamic covalent networks.
However, developing fiber-reinforced vitrimer composites for aeronautical applications with high mechanical performance and processable by conventional manufacturing processes remains highly challenging. In this work, a fully recyclable, bio-based epoxy vitrimer is developed and optimized to address these challenges. The proposed vitrimeric system achieves a tailored balance among mechanical strength, thermal stability, and processability required by standard aerospace manufacturing routes. The results highlight the potential of bio-based epoxy vitrimers as sustainable matrices for next-generation fiber-reinforced composites, enabling recyclability and reparability without compromising manufacturability or structural performance.

2. Methodology

The epoxy systems investigated in this study were formulated using GreenPoxy-28 (GP), a bio-based reactive epoxy monomer with a bio-based carbon content of 28%, supplied by Sicomin (Châteauneuf-les-Martigues, France). As a curing agent, 4-aminophenyl disulfide (4-AFD), provided by Sigma-Aldrich (St. Louis, Missouri, USA), was employed.
An epoxy equivalent weight (EEW) of 178.9 g·mol^{-1} was adopted for GP, and the formulations were prepared following a stoichiometric ratio between the epoxy precursor and the curing agent. Taking into account the number of active hydrogen atoms in the 4-AFD molecular structure, 1.000 g of epoxy precursor was combined with 0.347 g of curing agent. The hardener was incorporated into the epoxy system under magnetic stirring at 120 °C for 10 minutes to ensure complete dissolution and homogenization.
Subsequently, the obtained epoxy formulations were degassed at 80 °C for 1 hour and cast into metallic molds. The curing process was carried out via a two-step thermal cycle consisting of 1 hour at 150 °C followed by 1 hour at 180 °C.
Fourier Transform Infrared (FT-IR) spectroscopy was performed using a Bruker Vertex 70 spectrophotometer over the wavenumber range of 4000–400 cm^{-1}, with a resolution of 2 cm^{-1} and 32 accumulated scans. Thermogravimetric analysis (TGA) was conducted using a Mettler Toledo TC-10 thermobalance. Differential Scanning Calorimetry (DSC) measurements were carried out using a Mettler Toledo DSC 822e under a nitrogen atmosphere. In addition, Dynamic Mechanical Analysis (DMA) was performed to evaluate the thermomechanical properties of the epoxy systems.
Furthermore, vitrimer-based carbon fiber-reinforced composites were manufactured using the developed epoxy formulation in combination with woven carbon fabric relevant to the

aerospace sector. The mechanical performance of the resulting composites was evaluated through static tensile testing.

3. Conclusions

In the present study, a bio-based epoxy vitrimer exhibiting a high glass transition temperature (exceeding 150 °C) was successfully developed. The resin system was comprehensively characterized in order to optimize the curing protocol. Furthermore, carbon fiber-reinforced vitrimeric composites were fabricated via a compression molding process, and their mechanical properties were systematically evaluated to assess their performance.
The incorporation of dynamic covalent bonds within the polymer network imparts intrinsic reparability and recyclability to the material. Healing capabilities were investigated by comparing the mechanical performance of laminates before and after the introduction of controlled damage. In addition, recyclability was explored through thermoforming processes.
The experimental results demonstrate that the developed composites can be reshaped multiple times, thereby enabling the reuse of the laminates and expanding their potential applications.

Acknowledgment: The activities were performed in the frame of the project "H2STEM" (CUP: F57G25000130006) funded by the Italian Ministry of the Environment and Energy Security (MASE).

Towards Smart Nylon: Electrically Responsive PA6 Composites for Aerospace Applications

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1. Introduction

Nylon is widely used in engineering and aerospace applications for its high tensile strength, toughness, wear resistance, and impact absorption [1]. When reinforced with glass fibers, nylon composites offer significant weight savings relative to metallic components while maintaining structural integrity, making them suitable for aircraft components such as covers, housings, engine parts, and wing flaps [2]. Incorporating carbon fillers via advanced processing techniques enhances crystallization, thermal stability, and mechanical performance, while also imparting electrical conductivity and self-heating via the Joule effect [1,3]. This study investigates the electrical response of Polyamide 6 filled with expanded graphite under mechanical, thermal, and humidity stimuli. In highly controlled aerospace environments, excessive humidity can cause plasticization, reduce stiffness and strength, alter stress-sensing signals, and produce unpredictable material behavior. Therefore, minimizing moisture absorption through Joule heating and continuously monitoring humidity levels within nylon-based components are essential to ensure accurate stress sensing, consistent performance, and overall system safety.

2. Methodology

The study investigates the development of multifunctional self-sensing nanocomposites

based on Nylon 6 filled with expanded graphite (EG). The material was designed to respond electrically to external stimuli such as mechanical strain, temperature, and humidity through tunneling conduction mechanisms. Structural investigation demonstrated the presence of oxygen-containing functional groups that improve compatibility with the nylon matrix. Nanocomposites containing different EG concentrations were produced through melt mixing, and their electrical conductivity was analyzed according to percolation theory. A sharp conductivity increase occurred near the percolation threshold, identified at approximately 9.4 wt% filler concentration. A composition containing 20 wt% EG was selected for sensing investigations because it provided an optimized behavior with respect to conductivity and sensitivity.

3. Results and conclusions

Mechanical tests revealed strong piezoresistive behavior, with resistance increased exponentially under strain, and the gauge factor reached 62, exceeding that of conventional strain gauges. Cyclic loading tests also showed the ability to detect irreversible plastic deformation through residual resistance variations, highlighting the material's potential for structural health monitoring.
Temperature-sensing experiments between 20 °C and 120 °C showed stable positive temperature coefficient behavior below 80 °C, with a sensitivity of 0.175 %/°C. Above the glass transition temperature of nylon, resistance decreased due to conductive network rearrangements and increased electron mobility. Cyclic thermal tests confirmed excellent reproducibility and stability. Humidity sensing demonstrated that graphite reduced water uptake and diffusivity compared to pure nylon. However, absorbed water strongly influenced resistance, causing variations up to 250% due to swelling and water molecules acting as barriers to electron tunneling. Joule heating successfully regenerated the sensor, restoring its sensing capability without permanent structural damage.

Acknowledgment: This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101091828

Towards Greener Aeronautical Composites: The Promise of Electrocuring

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1. Introduction

The manufacturing of aeronautical fiber-reinforced polymer composites traditionally relies on energy-intensive thermal curing processes, such as autoclave or oven curing, which impose significant limitations in terms of energy dissipation, costs, and sustainability [1,2].
Electrocuring has emerged as a promising alternative manufacturing approach, leveraging Joule heating generated by electrically conductive reinforcement phase or nanofillers, such as carbon fibers or embedded conductive nanoparticles, to achieve in situ resin curing [1,2]. This approach is highly compatible with out-of-autoclave manufacturing routes.
Electrocuring for aeronautical composite structures enables rapid curing and reduces energy consumption. However, several technical and technological challenges still hinder widespread industrial adoption. This research analyzes the advantages with respect to traditional manufacturing processes and the future challenges. Particular attention is given

to the interplay among electrical, thermal, and cure-kinetics phenomena, which critically influence final composite quality. Overall, electrocuring represents today a viable and innovative pathway toward more efficient, flexible, and sustainable manufacturing of next-generation aeronautical composites, especially when combined with advanced resin systems and smart process monitoring strategies.

2. Methodology

In this study, aeronautical thermosetting resin, based on "3,4-Epoxycyclohexylmethyl-3',4'-epoxycyclohexane carboxylate" precursor and methyl hexahydro phthalic anhydride hardener, has been filled with carbon nanotubes (CNTs). CNTs were dispersed into the precursor at a percentage of 3 % wt./ wt. through ultrasonic dispersion for 20 min at 100◦C. After the sonication, the hardener was added to the mixture with a weight ratio precursor/ hardener of 1/1. Then, the mixture was mixed for 20 min at room temperature by magnetic stirring and poured into a silicone mold with a size of 50 mm × 30 mm × 10 mm. The samples were degassed for 1h at room temperature under vacuum. and then cured in two different modes:

i) conventional heating cycle in an oven (1 h at 80◦C + 20 min at 120◦C + 1 h at 180◦C);

ii) electrocuring process.

For the electrocuring process, the silicone mold was equipped with two copper electrodes with a thickness of 80µm connected to a power supply. All the Joule heating curing tests in the present research work have been performed in direct current. The heating maps were captured with a thermal infrared camera, while a thin wire thermocouple (Type T) positioned at the center of the mold was used to monitor the temperature of the mixture. The electrical current signal was recorded during the entire curing process. A scheme of the electrocuring process has been reported in Figure 1.

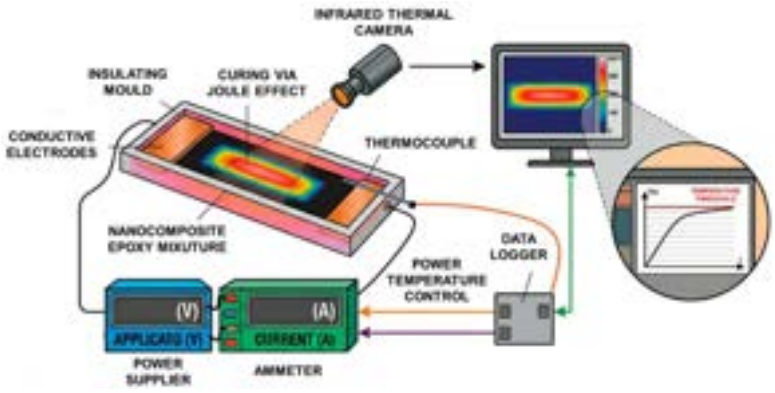


Figure 1. *Scheme of electrocuring process.*

Differential scanning calorimetry (DSC), corroborated by FTIR analysis, was used to study the curing kinetics of the epoxy mixture and to identify the different stages of the curing process during electrocuring.

3. Conclusions

Nanocomposites containing CNTs were successfully cured via electrocuring and compared with conventional oven curing, highlighting a paradigm shift in composite manufacturing. By exploiting the intrinsic electrical conductivity of the CNT network, heat is generated directly within the material through resistive dissipation, enabling volumetric and highly efficient heating. Unlike traditional methods, where heat must be transferred from the external environment, leading to significant losses due to thermal gradients and heating of surrounding equipment [3], electrocuring minimizes energy inefficiencies by localizing heat generation within the reactive system.

This results in a faster temperature rise, improved microscale uniformity, and a substantial reduction in overall energy consumption. Moreover, the direct coupling between electrical input and thermal response allows precise control of the curing process. Overall, electrocuring emerges as a highly energy-efficient and sustainable alternative, capable of reducing processing energy while maintaining high curing performance, thus offering strong potential for next-generation composite manufacturing.

Acknowledgment: This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101091828.

From Waste to Resource: Green Chemical Recycling of Bio Based Epoxy Composites

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[2]University of Basilicata, Italy

1. Introduction / Objectives

Epoxy thermosetting composites are widely employed in high-performance sectors such as aerospace, wind energy, and automotive engineering; however, their permanent crosslinked network severely limits end-of-life recycling options. Conventional recycling routes, including mechanical grinding and thermal treatments, typically result in significant material degradation, downcycling, or high energy consumption, thereby constraining their contribution to a circular composites economy. Among the available strategies (Figure 1), chemical recycling has emerged as the most promising approach for epoxy thermosetting composites, owing to its ability to selectively depolymerize the epoxy matrix while preserving the structural integrity of the reinforcing fibers.

This work is focused on the superior material recovery performance of chemical recycling processes such as solvolysis. Unlike mechanical recycling, which produces low-value fillers, and thermal recycling, which often damages fibers and fully sacrifices the matrix, chemical recycling enables the recovery of carbon and glass fibers with near-virgin mechanical properties and clean surface chemistry.

2. Methodology

The experimental methodology adopted to achieve the objectives is based on a

multidisciplinary approach integrating various analytical and experimental techniques. First, thermogravimetric analyses (TGA) were conducted to monitor the weight loss of the samples as a function of temperature, allowing for the assessment of the thermal stability and depolymerization of the fibers. Second, Scanning Electron Microscopy (SEM) and Energy-Dispersive Spectroscopy (EDS) were used to microscopically analyze the recovered fibers and compare them with virgin fibers, verifying surface cleanliness and morphological characteristics. Finally, structural and functional characterization analyses were conducted, including X-Ray Diffraction (XRD) to study crystalline organization, and electrical conductivity analyses using 4-wire sensing and Tunneling Atomic Force Microscopy (TUNA) techniques to evaluate the distribution and nature of the conductive domains at the nanoscale. In addition to these characterizations, we also performed mechanical analyses (tensile and flexural tests) and dynamic thermal analysis (DMA) to determine the mechanical and thermal properties of the material, and Fourier Transform Infrared (FT-IR) analyses to chemically characterize the oligomers obtained from the depolymerization process.



Figure 1. *Chemical Recycling of Epoxy Composites*

3. Results / Conclusions

Despite challenges related to process complexity, solvent management, and scalability, chemical recycling outperforms alternative solutions in terms of fiber quality retention and alignment with circular economy principles. This work describes the recycling procedure of carbon fiber reinforced composite made of bio-based epoxy resin. The experimental activity demonstrates that it is possible to recycle high-performance thermosetting composites at mild temperatures and ambient pressure using green solvents.

The performed analysis highlights that chemical recycling is able to provide a quality of the

reinforcing fibers similar to that of the virgin fibers and the oligomers derived from the resin matrix with a molecular weight of the same magnitude order as the initial epoxy precursor. Furthermore, chemical routes offer the unique potential to valorize resin-derived degradation products, thereby enhancing overall material circularity.

Acknowledgement: This research was funded by the European Union's Horizon Europe research and innovation program under Grant Agreement No. 101091828.

Synthesis and development of inherently highly flame-resistant nylon for aerospace applications

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1. Introduction / Objectives

Nylon 6,6 is a powerhouse in the synthetic materials industry. As a thermoplastic linear polyamide, it has secured a massive niche by being both high-performing and budget-friendly. Its technical profile is impressive, characterized by toughness, elasticity, heat resistance, and inherent self-lubricating properties.
However, it faces a significant drawback: fire safety. With a Limiting Oxygen Index (LOI) between 20% and 22%, it ignites easily in normal air. Since weight reduction is a top priority in aviation, Nylon 6,6 is an essential resource for trimming aircraft weight and improving fuel economy by replacing traditional metal hardware. It is typically found in cabin interiors, wiring, mechanical parts, and fasteners. To meet strict flight safety regulations, aerospace-grade Nylon 6,6 is almost always glass-reinforced and treated with flame retardants. This ensures the material remains self-extinguishing and does not melt or spread flames during an emergency.

2. Methodology

This research addresses the technical challenge of making nylon 6,6 fire-resistant without sacrificing its structural integrity. Traditionally, manufacturers use additives, mixing flame-retardant compounds into the polymer. However, these often require high "loadings" to be effective, which unfortunately weakens the material's mechanical strength and makes it harder to process.
To solve this, we have decided on chemical modifications. Instead of mixing in an additive, we have covalently integrated flame-retardant functional groups directly into the macromolecular structure. While this is synthetically more complex, it would allow the polymer to retain its intrinsic properties, such as toughness and flexibility, while achieving significantly better fire resistance. The study focused on the synthesis and copolymerization of two novel phosphorus-containing diamines: bis(3-((2-aminoethyl)amino)phenyl)(methyl)phosphine oxide (dMPO) and bis(3-((2-aminoethyl)amino)phenyl)(phenyl)phosphine oxide (dPPO). These new compounds are derived from bis(3-(aminophenyl)(methyl)phosphine oxide (BAMPO) and bis(3-

(aminophenyl)(phenyl)phosphine oxide (BAPPO), two known phosphine oxides recognized for their fire-stopping capabilities. We used these new diamines as comonomers in process polycondensation to synthesize nylon 6,6. By reacting these diamines with adipoyl chloride and hexamethylenediamine, we successfully synthesized modified polyamide copolymers (Figure 1).

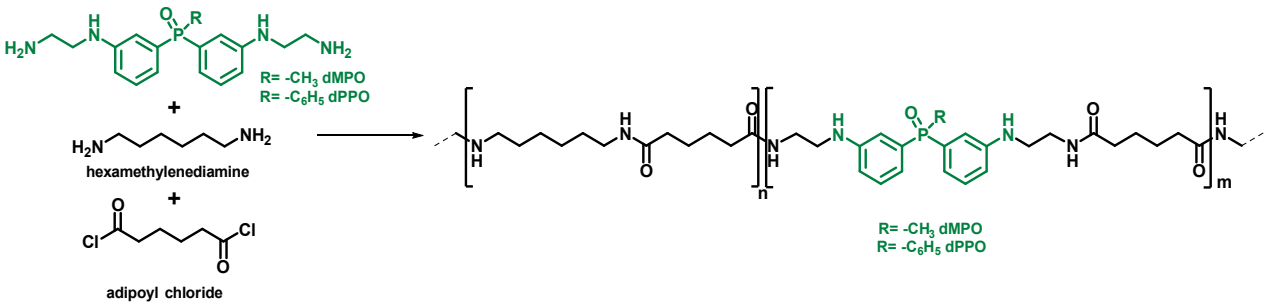


Figure 1. *Synthesis of nylon 6,6 with flame-retardant compounds.*

Copolymers with different ratios of comonomers were prepared to understand how their concentrations affected the final product. The copolymers were prepared using different ratios of diamines: 60/40 and 30/70 (dMPO or dPPO/hexamethylenediamine) while the ratio of the diamines to the adipoyl chloride was 1.9. All synthesized products, monomers and polymers, were extensively characterized by ^{1}H- and ^{13}C-NMR, FT-IR, X-ray diffraction, differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA). TGA results indicate that while standard nylon 6,6 and its monomeric precursors decompose almost completely by 450 °C, the incorporation of dMPO or dPPO into the polymer chain significantly alters its thermal stability.

3. Results / Conclusions

In summary, this work highlights a "re-engineering" of the polyamides at a molecular level. By building phosphine oxide derivatives directly into the polymer chain, we aimed to create a high-performance polyamide that is inherently safer and more fire-resistant than traditional versions, potentially expanding its applications in demanding sectors such as aerospace and electronics. Unlike nylon 6,6, these phosphorus-containing copolymers exhibit significantly greater thermal resilience. Even when heated to 800 °C, they do not degrade completely, instead, they form a stable char layer. Three modified copolymers retain at least 10% of their original mass as residue, while one sample proves particularly robust by leaving behind more than 20% char. These results suggest that the integration of phosphorus-functionalized diamines is highly effective in shielding the material from total thermal decomposition.

Impact Assessment Studies in Aviation R&I: A Systematic Approach to Evaluating Technological and Operational Innovations

Chaired by:
Mr. Patrick Ratei & Mr. Prajwal Prakasha (German Aerospace Center (DLR), Germany)

Enabling End-to-End Aviation Impact Assessment through a Digital Collaborative Framework

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German Aerospace Center (DLR), Germany

1. Introduction / Objectives

The transition toward climate and societal sustainability in aviation requires impact assessments that span the full Air Transport System (ATS), from aircraft technology and fleet composition to airport operations, environmental effects, and policy implications. No single discipline or institution can cover this scope, thus motivating the development of a collaborative digital framework that integrates distributed simulation tools, data, and methodologies contributed by multiple partners. The Impact Monitor (IM) framework established such a foundation, combining a central data model (CPACS), distributed workflow execution (RCE), and an interactive dashboard.
This paper presents the evolution of that foundation toward a genuinely *end-to-end* collaborative assessment lifecycle. Three extensions are introduced: (i) MBSE-based requirements modeling enabling traceability and validation, (ii) systematic integration of Uncertainty Quantification (UQ) and multi-fidelity modeling on top of existing simulation workflows, and (iii) an enhanced KPI visualization dashboard for decision support. The framework is demonstrated on four impact assessment studies within the IM2 project.

2. Methodology

The framework retains the core architecture of IM : CPACS as a standardized data model spanning aircraft, airport, and ATS levels ; RCE as a distributed workflow execution environment with secure remote model integration via Uplink and BRICS; and a web-based collaborative dashboard. The present work extends this architecture along the assessment lifecycle, from requirements definition through validation, and broadens its analytical scope through uncertainty and fidelity management.
Requirements modeling. A dedicated in-house tool (ARMADE) provides a graphical, MBSE-based environment for capturing stakeholder needs and requirements supporting users with the underlying formalism. Requirements are stored as structured, traceable artifacts that feed the validation step at the end of the assessment cycle. Workflow construction itself remains driven by the MDAO Workflow Design Accelerator software MDAx .
Uncertainty Quantification and multi-fidelity. UQ is treated as a non-intrusive layer wrapped around existing deterministic workflows. Two complementary methodologies, uqStudio and OpenTURNS , are made available within the framework, enabling propagation of input uncertainties onto KPIs without redesigning the underlying simulation chains. Multi-fidelity modeling is handled by exploiting the framework's existing modularity: lower-fidelity models can be substituted with higher-fidelity counterparts within a workflow as study maturity

progresses, balancing computational cost and accuracy. Closer integration of UQ outputs into the dashboard layer is identified as future development.

Application and dashboard. The integrated framework is exercised on four preliminary impact assessment studies covering aircraft technology and operations at ATS, with detailed overviews of each study reported in dedicated sibling publications . The dashboard has been extended with refined KPI representations and interactive exploration to support trade-off analysis across the four studies, providing an accessible decision-support layer for aerospace researchers, industry, and policy stakeholders.

3. Results / Conclusions

The extended framework has been successfully applied on the four IM2 preliminary impact assessment studies, demonstrating its readiness to support coordinated multi-institutional assessments from requirements definition through KPI visualization. Beyond the technical execution, the work has produced consolidated lessons that have already fed back into methodological refinement: practical conventions for managing CPACS schema extensions across partners, scalable practices for coordinating large collaborative workflows with heterogeneous model contributions, and standardized training and example materials that reduce onboarding effort for new partners and models.

The framework provides European aviation research and policy stakeholders with a transparent, integrated, and uncertainty-aware infrastructure for evaluating technological and operational decisions against environmental and societal KPIs. Ongoing work focuses on tighter coupling between UQ outputs and the dashboard, requirements-driven workflow construction, and consolidation of CPACS ATS-level extensions toward a public release for broader community adoption.

Acknowledgement: The research has been performed within the Impact Monitor 2 project, funded by European Union's Horizon Europe Research and Innovation program (Grant Agreement No 101193001).

Operationalizing Impact Assessment Studies: from Study Definition to Implementation

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1. Introduction / Objectives

The main objective of the EU project "Impact Monitor 2" is to deliver a coherent and holistic Toolbox and Framework (including their application to impact-assessments of R&I inspired by Clean Aviation and SESAR) that will be the reference choice for the definition and assessment of environmental, climate and competitiveness policy options of European aviation R&I and regulatory measures.

This paper addresses the overall process from the framing of all the studies scenarios with the Impact Monitor Toolbox **Error! Reference source not found.** to the implementation and operation in the collaborative Framework of Impact Monitor 2.

2. Methodology

The Impact Monitor Toolbox **Error! Reference source not found.** explains what conducting holistic impact assessments entails. It provides a systematic approach of the complete cycle of performing impact assessments of R&I in aviation. At the beginning of the project, Impact Monitor Toolbox has been applied to the four-preliminary impact-assessments ending with the framing of:

- Two studies covering the preliminary impact-assessment at air-transport system (ATS) level and at airport level, respectively, of a technological innovation. These studies are inspired by new aircraft concepts developed in Clean Aviation
- Two studies covering the preliminary impact-assessment at air-transport system (ATS) level and at airport level, respectively, of an operational innovation. These studies are inspired by new operational developed in SESAR

At that stage, several activities must be performed in order to achieve the implementation of different workflows enabling the assessment of the identified metrics.
A first activity deals with the identification and integration of models tailored for each study. Even though some models were identified in the scope Impact Monitor Toolbox, they should all fulfil a list of requirements such as alignment with the latest scientific knowledge and be developed and maintained following best practices in research software engineering. In addition, they should be made compliant with the Framework in terms of interoperability with the central data model (CPACS) and with their access through the distributed workflow execution framework (RCE) already used in Impact Monitor.
A second activity deals with the refinement of all scenarios entailed by the studies objectives, especially regarding the Technology innovation stream . First a fleet forecast scenarios should be proposed relaying on a set of aircraft concepts covering to the 12 ICAO seat classes segmentation, from regional, narrow body to wide body jets. In addition, for each aircraft of each class of each scenario, aircraft models are meant to be created to serve as inputs for the assessment studies fulfilling two requirements: being compliant with the framework standardized data exchange format and being tailored to the assessment levels in terms of granularity of information, regarding noise and emissions information.
Last, the studies are bound to consider new framework capabilities such as UQ and multi-fidelity modeling in their workflows, in consistency with the studies objectives.

3. Results / Conclusions

The overall approach has been successfully applied on the four IM2 impact assessment studies, allowing the refinement of specifications that constitute the basis for the next steps: set-up, execution and analysis of the studies, through the further application of the Impact Monitor Toolbox and Framework.

Acknowledgement: The research has been performed within the Impact Monitor 2 project, funded by European Union's Horizon Europe Research and Innovation program (Grant Agreement No 101193001).

Multi-Fidelity Aircraft Modelling for Integrated Impact Assessment of Technology R&I

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1. Introduction / Objectives (up to 150 words)

The aviation sector faces increasing pressure to reduce environmental impacts while meeting future air transport demand, requiring the integration of advanced technologies and alternative energy systems into aircraft design. This study presents a multi-fidelity modelling framework for integrated impact assessment of current baseline aircraft and future concept aircraft expected to enter service (EiS) around 2040 and 2055 (±5 years), as illustrated in the technology roadmap in Figure 14. The analysis considers progressive implementation of emerging technologies including advanced propulsion concepts, hybrid-electric and fully electric architectures, and alternative fuels with particular emphasis on hydrogen. The work integrates aircraft mission modelling, engine cycle analysis with emission index estimation, and airport noise assessment through Noise–Power–Distance (NPD) table generation. Open-source and in-house tools, including SUAVE, AirCADia, TurboMatch, Dynamo3, NASA ANOPP2, and FLOPS, are combined to enable a comprehensive assessment of future aircraft performance, emissions, and noise impacts.



Figure 14. *Technology roadmap*

2. Methodology (up to 350 words)

This kind of research, which involves a variety of tools (and possibly different levels of fidelity depending on the aircraft aspects that are under study greatly benefits from a common model such as CPACS [6], which facilitates the exchange of information between them. Using a common model, in turn, imposes the requirement that every tool be able to read CPACS files or use a converter to obtain the necessary information. Similarly, tools that produce an output to be consumed by other tools (e.g. aerodynamic results) need to be able to update the CPACS with their output as well.

Conceptual aircraft design tools (SUAVE and AirCADia) use their own common model that is used to define the aircraft components, relations, analyses and results including mass, centre of gravity, aerodynamic, propulsion, mission and stability. These tools combine Torenbeek and Raymer models, with software such as XFOIL, FLOPS and ANOPP. A converter has been developed that contains the aircraft geometry and components, and the analyses results. Other tool required specific inputs and a converter from CPACS to the specific format becomes necessary. Dynamo3, the 4D trajectory simulation tool used for this study requires an input file for each aircraft type in a specific format equal to the one used in BADA. Therefore, a converter from CPACS to BADA is needed. For this purpose, a converter named *cpacs2bada* has been developed. This converter extracts the required information from the geometrical and analysis information contained in the CPACS file, including mass breakdown, aerodynamic and propulsion analyses. In particular, the aerodynamic and propulsion coefficients are obtained via dataset filtering and weighted least-square regression, which adapts the higher fidelity data to the lower fidelity BADA model.
Figure 15 presents an overview of the workflow, where SUAVE/AirCADia aircraft definition and compatible tools are connected to the rest of CPACS tools using the Aircraft Sizing Module to CPACS converter. Similarly, the figure shows how existing tools such as Dynamo 3 can be made CPACS compatible, in this case via the cpacs2bada converter.



Figure 15 *Tools workflow*

3. Conclusions (up to 150 words)

This study demonstrates the applicability of an integrated multi-fidelity framework for assessing the environmental and operational impacts of future aircraft technologies across different entry-into-service scenarios. The framework enables comparison between baseline and future aircraft concepts incorporating advanced propulsion, e.g., hydrogen fuel, and hybrid/full-electric architectures. By integrating mission performance, emissions, and noise analyses within a common workflow, it supports identification of technology trade-offs and provides a flexible approach for future aviation assessment and technology roadmapping.

.Acknowledgement: The research has been performed within the Impact Monitor 2 project, funded by European Union's Horizon Europe Research and Innovation program (Grant Agreement No 101193001).

Preliminary Impact Assessment Studies of Flight Operational R&I: Current Progress and Insights

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1. Introduction / Objectives

The main objective of the EU project "Impact Monitor 2" is to deliver a coherent and holistic Toolbox and Framework (including their application to preliminary impact-assessments of R&I inspired by Clean Aviation and SESAR) that will be the reference choice for the definition and assessment of environmental, climate and competitiveness policy options of European aviation R&I and regulatory measures. This paper addresses two applications of the Toolbox and Framework to operational R&I's in aviation. The first one is a preliminary assessment at air-transport system level of evaluating uncertainties in optimising trajectories for contrail avoidance, and the second one is a preliminary assessment at airport level of the impact of reduced separation minima for approach and departure phases.

2. Methodology

Inspired by EC's Better Regulation Toolbox, the Impact Monitor Toolbox explains what conducting holistic impact assessments entails. It provides a systematic approach of the complete cycle of performing impact assessments of R&I in aviation.
Applying the Impact Monitor Toolbox, each of the two preliminary impact-assessments of an operational R&I in aviation is specified with a focus on the following questions:

- What R&I is to be assessed and what does it encompass?
- In what context is the R&I developed and what problem does it aim to (help to) alleviate or solve?
- What does this R&I aim to achieve and what is its objective?
- What is the development stage of the R&I?
- What stakeholders are (or could be) involved in, served by and/or impacted by the R&I?
- What is the year for the Baseline Scenario and what is (are) the year(s) for the Reference and R&I Scenario(s) for this R&I?
  The Baseline Scenario is the scenario that reflects the actual state in a historic year of the part of the air-transport system that is relevant to the (assessment of the) R&I. Starting from the Baseline Scenario, a Reference Scenario ('no-change' or 'business-as-usual' scenario) is a projection of this part of the air-transport system in a future year to be considered in the impact assessment, without the introduction of the R&I. The R&I Scenario is the Reference Scenario, but with the introduction of the R&I. The impacts in the R&I Scenario are assessed against those in the Reference Scenario.
- What key-performance indicators are to be quantified for the R&I?
- What instruments (e.g. EU Directives, international (scientific) standards, and internationally recommended and best practices) are applicable for assessing the R&I?
- What are proposed models (with models chain) and what are identified model gaps?
- What data gaps are identified (especially data from outside the consortium or data from another study)?

3. Results / Conclusions

To demonstrate the Impact Monitor Toolbox and Framework, two preliminary impact assessments of advanced aircraft technologies to be introduced in future fleets have been specified:

- Evaluating the environmental impact of Emissions in future global fleets by introducing new concept aircraft gradually until the year 2070 into the fleet with the aim also to assess the climate impact;
- Assessing environmental impact of Emissions and noise in a future airport fleet for the generic airport CAEPport by introducing new concept aircraft gradually until the year 2070 into the fleet.

The study specifications constitute the basis for the next steps: Set-up, execution and analysis of the studies, through the further application of the Impact Monitor Toolbox and Framework

Acknowledgement: The research has been performed within the Impact Monitor 2 project, funded by European Union's Horizon Europe Research and Innovation program (Grant Agreement No 101193001).

Preliminary Impact Assessment Studies of Aircraft Technology R&I: Current Progress and Insights

Alf Junior*[1], *Michel van Eenige*[1], *Sreyoshi Chatterjee, Maximilian Clococeanu, Zvitlana Zhukovska, Andrea Mancini, Patrick Ratei, Peter Hoogers, Ronald Grosmann, Claire Sarrat, Thierry Lefebvre, Jordi Pons Prats, David De La Torre, Inge Mayeres

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1. Introduction / Objectives

The main objective of the EU project "Impact Monitor 2" is to deliver a coherent and holistic Toolbox and Framework (including their application to preliminary impact-assessments of R&I inspired by Clean Aviation and SESAR) that will be the reference choice for the definition and assessment of environmental, climate and competitiveness policy options of European aviation R&I and regulatory measures. This paper addresses two applications of the Toolbox and Framework to operational R&I's in aviation. The first one is a preliminary assessment at air-transport system level of evaluating uncertainties in optimising trajectories for contrail avoidance, and the second one is a preliminary assessment at airport level of the impact of reduced separation minima for approach and departure phases.

2. Methodology

Inspired by EC's Better Regulation Toolbox, the Impact Monitor Toolbox explains what conducting holistic impact assessments entails. It provides a systematic approach of the complete cycle of performing impact assessments of R&I in aviation.

Applying the Impact Monitor Toolbox, each of the two preliminary impact-assessments of an operational R&I in aviation is specified with a focus on the following questions:

- What R&I is to be assessed and what does it encompass?
- In what context is the R&I developed and what problem does it aim to (help to) alleviate or solve?
- What does this R&I aim to achieve and what is its objective?
- What is the development stage of the R&I?
- What stakeholders are (or could be) involved in, served by and/or impacted by the R&I?
- What is the year for the Baseline Scenario and what is (are) the year(s) for the Reference and R&I Scenario(s) for this R&I?
  The Baseline Scenario is the scenario that reflects the actual state in a historic year of the part of the air-transport system that is relevant to the (assessment of the) R&I. Starting from the Baseline Scenario, a Reference Scenario ('no-change' or 'business-as-usual' scenario) is a projection of this part of the air-transport system in a future year to be considered in the impact assessment, without the introduction of the R&I. The R&I Scenario is the Reference Scenario, but with the introduction of the R&I. The impacts in the R&I Scenario are assessed against those in the Reference Scenario.
- What key-performance indicators are to be quantified for the R&I?
- What instruments (e.g. EU Directives, international (scientific) standards, and internationally recommended and best practices) are applicable for assessing the R&I?
- What are proposed models (with models chain) and what are identified model gaps?
- What data gaps are identified (especially data from outside the consortium or data from another study)?

3. Results / Conclusions

To demonstrate the Impact Monitor Toolbox and Framework, two preliminary impact assessments of operational R&I's have been specified:

- Evaluating the uncertainties in the optimisation process of trajectories for contrail avoidance, with the aim to enable decision making for daily weather situations by airspace users;
- Assessing environmental, economic and societal impact of reduced separation minima for arrivals and departures, based on RECAT-EU-S-PWS and applied to the generic airport CAEPport.

The study specifications constitute the basis for the next steps: Set-up, execution and analysis of the studies, through the further application of the Impact Monitor Toolbox and Framework.

Acknowledgement: The research has been performed within the Impact Monitor 2 project, funded by European Union's Horizon Europe Research and Innovation program (Grant Agreement No 101193001).

Assessing Near-Future Pathways for Sustainable Air Transport: An Impact Assessment Approach for Fleet Renewal and SAF Deployment

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1. Introduction / Objectives

The aviation sector is facing increasing pressure to accelerate the transition towards climate-neutral and socially sustainable operations. At the same time, higher education institutions are challenged to equip students with interdisciplinary competencies capable of addressing complex sustainability and impact assessment problems. The Impact Monitor 2 Academy addresses these challenges by creating a research-integrated educational approach that directly connects academic learning with ongoing European aviation research activities. Building upon the experiences and lessons learned from the previous Impact Monitor Academy, the Impact Monitor 2 Academy aims to strengthen the interaction between research, education, and innovation by involving students in real-world sustainability assessment tasks linked to aviation transformation pathways. The initiative enables students to contribute to scientific analyses, data-driven assessments, and communication activities while simultaneously developing transferable skills in sustainability evaluation, systems thinking, and collaborative research.

A key objective of the Impact Monitor 2 Academy is the generation of publication-worthy student contributions that can be disseminated through scientific conferences and journals, thereby increasing student participation in scientific discourse and fostering early-stage research excellence within the European aerospace ecosystem.

2. Methodology (up to 350 words)

The Impact Monitor 2 Academy follows a challenge-based and research-oriented educational approach embedded within the broader activities of the Impact Monitor 2 project. The programme combines academic supervision, collaborative project work, and direct integration into ongoing research workflows related to aviation sustainability and impact assessment. The methodology is structured around four main pillars:

1. **Research Integration:**
   Students are assigned to thematic research topics aligned with the objectives of the Impact Monitor 2 initiative, including multidimensional impact assessment of future aviation concepts. The topics are designed to address current challenges while ensuring academic rigor and relevance.
2. **Interdisciplinary Collaboration:**
   The Academy promotes cooperation among students from different academic backgrounds, including aerospace engineering, data analytics, and economics. This interdisciplinary structure mirrors the complexity of real-world aviation sustainability assessments and supports systems-level understanding.
3. **Scientific Mentorship and Methodological Training:**
   Participants receive guidance from researchers and project partners through workshops, seminars, and iterative feedback sessions. The training includes methodologies for impact assessment, scientific communication, data interpretation, and publication preparation.
4. **Dissemination and Scientific Contribution:**
   Student teams are encouraged to transform high-quality project outcomes into

scientific publications, conference abstracts, and dissemination materials. Publication readiness is assessed based on scientific novelty, methodological robustness, and relevance to ongoing aviation sustainability discussions.

The overall programme establishes a continuous feedback loop between education and research, allowing research projects to benefit from innovative student perspectives while simultaneously enhancing academic learning outcomes.

3. Results / Conclusions

The Impact Monitor 2 Academy demonstrates how research-driven education can strengthen both academic training and innovation capacity within the aerospace sector. Building on the successful experiences of the previous Impact Monitor Academy, the initiative establishes a scalable approach for integrating students into ongoing European research activities while generating scientifically relevant outputs.
Expected outcomes include enhanced student competencies in sustainability assessment, increased participation of young researchers in scientific dissemination activities, and the development of publication-quality contributions through student work addressing key aviation transformation challenges. Selected outcomes will be further refined and prepared for final dissemination during the current season leading up to the conference.

Acknowledgement: The research has been performed within the Impact Monitor 2 project, funded by European Union's Horizon Europe Research and Innovation program (Grant Agreement No 101193001).

Digitalization of Manufacturing, sustainable manufacturing, multifunctional structure and MRO

Chaired by:
Mr. Georgios Bampanis (European Climate, Infrastructure and Environment Executive Agency - CINEA)

Towards LES-Assisted Turbomachinery Design

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1. Introduction / Objectives

The aerodynamic design of turbomachinery components relies predominantly on Reynolds-averaged Navier-Stokes (RANS) simulations. However, the drive towards ultra-efficient, low-emission propulsion increasingly pushes components into regimes governed by transition, separation and strong wake mixing. In these regimes RANS modelling assumptions introduce uncertainties that propagate directly into design decisions. Scale-resolving simulations (SRS), in particular large-eddy simulation (LES), offer markedly higher predictive fidelity. Combined with the high-order solvers from academia, LES at industrial scale is increasingly within reach.

Yet their unsteady, statistical nature and the significantly higher cost compared to RANS still hinder the routine use of SRS as a primary optimization tool.
Within the European Horizon project Sci-Fi-Turbo, we aim to integrate SRS into the turbomachinery design process. We establish an automatic LES workflow and show the potential of high-fidelity SRS optimization compared to a RANS baseline. Building on that, we present approaches to reducing cost through multi-fidelity optimization and data-driven RANS modelling.

2. Methodology

The approach is demonstrated for a compressor cascade representative of a low-Reynolds-number outlet guide vane (LRN-OGV). This configuration exposes RANS modelling deficiencies through transitional and separated flow, yet at manageable cost for direct high-fidelity optimization. The objective is the reduction of profile losses at the aerodynamic design point (ADP) and at two off-design operating points at ±5° incidence, while constraining the outflow angles. The inflow is defined by a Reynolds number of 150,000 and a Mach number of 0.6. The blade is parameterized with the in-house tool BladeGen using 16 design variables describing the leading- and trailing-edge shapes, the suction-side and thickness-distribution splines, and the stagger angle.
A RANS-based optimization using the Menter SST $k-\omega$ turbulence model with the $\gamma - Re_\theta$ transition model serves as the baseline. Re-evaluating selected Pareto-optimal geometries with LES reveals systematic discrepancies: a shift in the predicted outflow angle means RANS-optimal designs can violate the imposed constraints at high fidelity. This motivates the incorporation of the high-fidelity solver into the optimization loop.
The central development of this work is a fully automated LES workflow that makes scale-resolving simulation usable as the flow solver within an optimization. Compared to steady-state RANS, the unsteady, statistical nature of LES places substantially higher demands on automation, and meeting these without manual intervention is the key enabler. The workflow couples DLR's optimization tool AutoOpti, using (Co)-Kriging surrogates, with the high-order discontinuous Galerkin solver of DLR's code TRACE, run remotely on the LUMI supercomputer. It integrates automatic meshing and setup, transient detection, sampling-error quantification, convergence monitoring, and inflow-Mach-number control, allowing the optimization to proceed without manual intervention.
On this basis, a fully LES-based, surrogate-assisted optimization is performed, seeded from the Pareto front of a RANS pre-optimization. To reduce the high cost of pure-LES optimization, the workflow is then extended towards multi-fidelity optimization, enriching abundant RANS data with sparse LES samples, and towards data-driven RANS modelling using LES data to improve the turbulence model. Both extensions pursue the same goal of retaining LES-level accuracy at substantially reduced cost, with first results presented at the conference.

3. Results

The automated LES workflow evaluated 129 candidate geometries, of which 108 satisfied all aerodynamic and geometric constraints, yielding a well-converged Pareto front (Figure 16). The selected best design lowers the loss at all three operating points relative to the baseline, while satisfying the outflow-angle constraints. Figure 17 shows the instantaneous flow field on the suction side, where the laminar separation bubble triggers transition to turbulence,

followed by a comparatively weak and narrow wake. Crucially, the LES-based optimization advances the Pareto front beyond the RANS-optimized designs re-evaluated with LES, underlining that reliable design decisions, especially at off-design, require high-fidelity LES rather than RANS alone.
Building on these results, the workflow is extended towards multi-fidelity optimization and data-driven RANS modelling, which aim to reach a similar accuracy at lower cost. Such automated LES-based workflows can enable design decisions for future engine concepts that lie beyond the reach of RANS today.

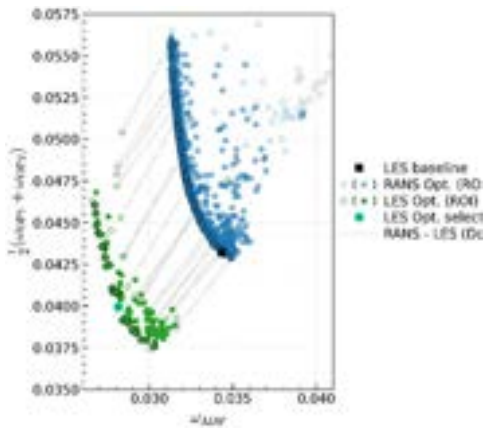


Figure 16: Databases of the low-fidelity RANS and high-fidelity LES optimizations alongside baseline and selected best geometry. Candidates within the region of interest (ROI) are indicated by filled markers, while the Pareto front is highlighted with framed markers.

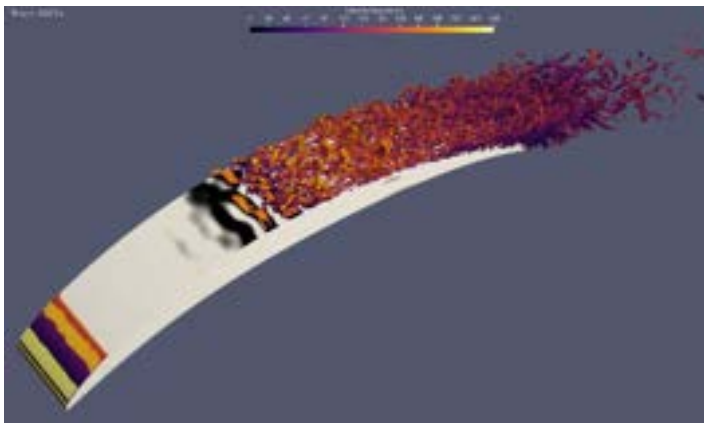


Figure 17: Instantaneous flow structures of the best member of the LES optimization at the ADP

Numerical Modelling of Fluid-Structure Interaction on Wings and Aeronautical Structures in Realistic Conditions

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1.Introduction / Objectives

The rapid evolution of aeronautical design and the pressing demand for environmentally responsible air transport require a new generation of predictive computational tools capable of accurately capturing complex physical phenomena such as fluid–structure interaction (FSI), aeroelasticity, and aeroacoustics. Aviation currently accounts for approximately 3.8% of

total European CO_2 emissions and nearly 14% of all transport-related emissions, making it the second-largest contributor to greenhouse gases after road traffic. Reducing emissions and mitigating noise pollution have therefore become essential priorities for both environmental and industrial reasons. To meet these challenges and quickly assess the validity and security of new aircraft concepts advanced numerical methodologies that can represent unsteady coupled aerodynamics and structural dynamics in realistic flight conditions are crucial. Within this context, the present work, developed under the Horizon Europe FALCON Project (Grant Agreement No. 101138305), introduces a comprehensive high-fidelity numerical framework dedicated to simulating and understanding Fluid-Structure Interaction (FSI) and associated aeroacoustic phenomena in aeronautical configurations. To tackle these challenges, we propose a solution coupling ProLB, a Lattice–Boltzmann-based fluid solver designed specifically for industrial test cases, to MSC Nastran, widely used finite element solver for structural mechanics, through the MSC CoSim coupling supervisor.

2.Methodology

The coupled ProLB–Nastran–CoSim framework provides a robust environment for studying both academic and industrial test cases involving two-way interactions between aerodynamic forces and elastic structures. ProLB is based on the Lattice Boltzmann Method (LBM), a mesoscopic approach derived from kinetic gas theory. Instead of solving directly the macroscopic Navier–Stokes equations, the LBM computes the evolution of a particle distribution function $f(x, c, t)$ on a discrete velocity lattice, from which macroscopic quantities such as density and velocity are obtained subsequently. This approach offers several advantages: simple Cartesian meshing, excellent parallel scalability, natural unsteadiness, and low numerical dissipation, all of which make it ideally suited for aeroacoustic computations. To further improve its stability and accuracy, ProLB employs a Hybrid Recursive Regularized (HRR) collision operator, which decomposes the particle distribution into equilibrium and non-equilibrium moments that are recursively computed. The HRR formulation ensures a stable representation of viscous stress tensors and suppresses non-physical numerical oscillations, which are critical when simulating turbulent flows over flexible or moving boundaries.

To represent complex geometries and solid surfaces immersed in the fluid, the framework integrates the Immersed Boundary Method (IBM). This approach eliminates the need for body-fitted grids or frequent mesh deformations by embedding the solid surface within the Cartesian fluid domain. At each Lagrangian point of the structure, a discrete Dirac delta function is applied to interpolate velocity and pressure fields between the Eulerian fluid grid and the Lagrangian structural mesh. The resulting hydrodynamic forces are then distributed back to the fluid solver to ensure momentum conservation. The IBM methodology has been extensively applied to LBM and extended to turbulent applications. It provides remarkable robustness and efficiency for arbitrary solid motions, including large deformations and oscillations, as encountered in aeroelastic wings or control surfaces.

The structural response is computed using MSC Nastran, which solves the finite element equations governing deformation, vibration, and stress distribution. Nastran's CQUAD4 plate elements and extensive modal capabilities make it particularly well suited to the dynamic analyses of thin aeronautical structures. The data exchange between ProLB and Nastran is coordinated by MSC CoSim, which manages synchronization between solvers through a Conventional Serial Staggered (CSS) explicit coupling scheme. In this iterative process, ProLB receives the updated nodal positions of the structure at each time step, computes the fluid loads using LBM and IBM, and transmits the resulting surface forces back to Nastran. The

structural solver then updates displacements and velocities that are returned to the fluid solver for the next iteration. Sub-cycling of the fluid and solid solver is possible in order to enhance the computation time.
To accurately represent turbulent flow features in the aerodynamic field, ProLB incorporates a Wall-Modeled Large Eddy Simulation (WM-LES) approach. The turbulence model employs a shear-improved Smagorinsky sub-grid formulation in the bulk of the flow, while near-wall regions are treated through an explicit power-law wall model that reconstructs velocity gradients without requiring excessive grid refinement. This hybrid approach ensures that the coupled solver can handle realistic Reynolds numbers while keeping computational costs manageable. The LBM-based LES is particularly advantageous for acoustic computations due to its low dissipation characteristics and naturally transient formulation.

3. Results / Conclusions

The Hron & Turek FSI2 benchmark is a widely recognized reference case for the validation of strongly coupled fluid-structure interaction (FSI) solvers. It involves the interaction between an incompressible flow and an elastic structure undergoing large deformations, making it particularly suitable for assessing both the accuracy and robustness of coupled numerical frameworks. The FSI2 test case has been primarly targeted for this study.

1. Problem Description
   The configuration consists of a two-dimensional channel flow past a rigid circular cylinder with an attached flexible beam located in its wake. The fluid domain is defined by a channel of length L = 2.5m and height H = 0.41m. A cylinder of diameter D = 0.1m is positioned at a distance of 0.2m from the inlet, and a flexible beam of length 0.35m 11 and thickness 0.02m is attached to the rear of the cylinder.
   The Reynolds number based on the cylinder diameter is Re = 100, ensuring a laminar but unsteady flow regime. The structural domain is modeled as an elastic material with density ρs = 103kg/m3, Young's modulus E = 1.4 × 106Pa, and Poisson ratio νs = 0.4.

2. Results
   The validation focuses on the dynamic response of the flexible beam, with particular attention to the tip displacement in the streamwise (x) and transverse (y) directions, as well as their associated oscillation frequencies. It should be noted that the results presented here are preliminary and are expected to be further improved through ongoing developments.
   Figure 1 and Table 1 present the time evolution and quantitative comparison of the beam tip displacement in both directions with respect to the original results from Hron & Turek published in [14]. The transverse displacement (y) shows good agreement with the benchmark, both in terms of oscillation amplitude and frequency, with only a slight underprediction observed. The dominant frequency is accurately captured, indicating a correct representation of the fluid-structure coupling mechanism. In contrast, the streamwise displacement (x) exhibits larger discrepancies. While the

mean amplitude remains of the same order of magnitude as the reference, the oscillation amplitude is slightly overpredicted and shows increased variability, with extreme values ranging approximately from $-0.03m$ to $0.025m$. The associated frequency is also marginally higher than the reference value. These differences suggest that the streamwise response is more sensitive to numerical parameters such as spatial resolution, coupling strategy, or time step, and therefore requires further investigation. It is worth noting that the transverse motion remains the dominant contribution to the structural response, and thus governs the overall fluid-structure interaction behavior. As a result, the observed discrepancies in the streamwise direction have a limited impact on the global dynamics of the system.

Overall, despite the preliminary nature of these results, the agreement obtained on the main quantities of interest demonstrates the capability of the proposed framework to reproduce the key features of the FSI2 benchmark. These results provide a solid basis for further improvements and confirm the potential of the method for the simulation of strongly coupled FSI problems.

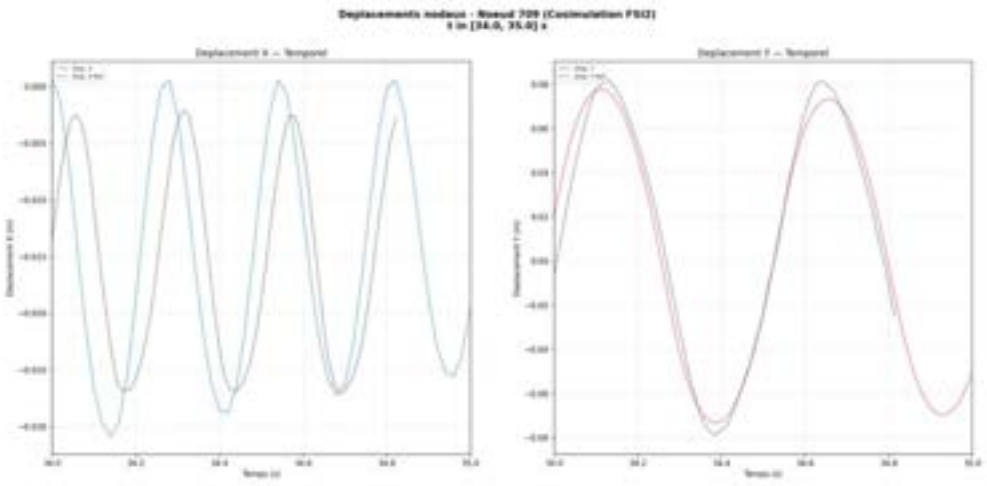


Figure 1 *- Time evolution of the beam tip displacement in the streamwise (x) and transverse (y) directions*

Study	A_x [m]	A_y [m]	f_x [Hz]	f_y [Hz]
Hron & Turek [14]	-0.014 ± 0.012	0.0012 ± 0.08	3.8	2.0
Present work	-0.015 ± 0.015	0.0031 ± 0.075	3.92	1.96

Table 1: Validation of the Hron & Turek FSI2 benchmark: comparison of beam tip displacement and oscillation frequencies.

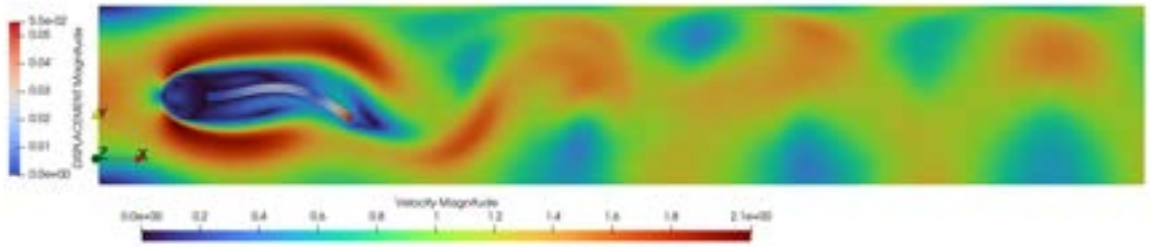


Figure 2 - Velocity magnitude in the flow and displacement of the beam

Overview the EU ROSAS project: RObust simulation Systems exploiting AI based turbulence models and hight-fidelity algorithmS

Vincent Couaillier
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1.Objectives

The aim of the ROSAS project is to address the development of advanced digital design technologies, which are needed to allow fast and reliable evaluations of innovative configurations identified in the Clean Aviation Strategic Research and Innovation Agenda (SRIA) of EU.
Within this framework, the project concentrates on innovative Computational Fluid Dynamics (CFD) simulation tools including coupling strategies for efficient online learning to improve models, numerical methods and fast surrogate models applicable to the full flight envelope. More specifically, ROSAS pursues two main objectives. The first one concerns the use of AI methodologies and high-order schemes to increase the numerical accuracy and efficiency of CFD simulation and optimization tools in order to accelerate compliance with the next generation of HPC infrastructures. The second one concerns the exploitation of machine learning-based techniques powered by statistical data and/or time series from High Fidelity (HiFi) simulations or experiments to develop and implement advanced turbulence models for complex phenomena.

2. Methodology

With the ambition to make significant progress on the core of the CFD kernel, a particular attention concerns the correct prediction of strongly separated flows necessary to cover the whole flight envelope or operating points of complex "industrial-like" configurations. The need to achieve a major breakthrough in the efficiency and accuracy of CFD models and algorithms is addressed by hybridizing high-order numerical schemes and advanced turbulence models with modern AI technologies. It is worth mentioning that the project also

benefits from the knowledge of AI methods for existing CFD models within the consortium, acquired in particular during the previous European project HiFi-TURB, as well as from the expertise of the consortium of partner teams working specifically on the mathematical aspects of high-order schemes and AI algorithms for turbulence.
The methodology used in ROSAS considers five main domains of activity following a workflow based on both a top-down and a bottom-up approach resulting in a V-cycle overall (Fig. 1). The partners first identified the key flow problems encountered in industrial applications that challenge current numerical and modelling technologies. A set of training test cases is then defined by identifying the key flow phenomena arising from these complex applications. Training test protocols are then implemented to isolate and faithfully reproduce the targeted phenomena in a controlled environment, thus enabling high-fidelity simulations or experiments with high-quality results and the storage of quantities of interest. In particular, the Reynolds number of the training test cases has been adapted to allow wall-resolution DNS and/or LES simulations (WRLES) and to resolve all relevant turbulence scales. The results are formatted with identification of the specific quantities of interest and gathered in open-source database. It should be noted that not all spatio-temporal turbulent fields are conserved, as this would lead to extremely large storage.

These new dataset, together with that already available in the CFD community, serve in the development and testing of novel data-driven numerical methods and turbulence models methodologies. Finally, these new technologies will be evaluated and assessed on application cases corresponding to challenging industrial phenomena and configurations.

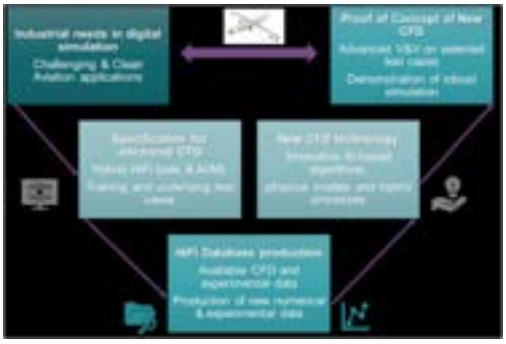


Figure 1: *Overall vision of the ROSAS project methodology*

3. Conclusion

Verification using a set of training test cases marks the first step of the project, enabling an accurate evaluation of the numerical scheme. To this end, a series of configurations were considered: aggressive S-shaped compressor transition ducts, a wing-body junction with corner flow separation, a transonic bump, a multi–element high-lift airfoil, and an adverse pressure gradient over a rounded step. In the first part of the project different Scale Resolved Simulations (SRS) for turbulent flows using either DNS or LES models with high-order methods were carried out to enrich the dataset that will be used to train new algorithms and Reynolds-averaged Navier-Stokes (RANS) turbulence models under development in the second part of the project.

Digital Twins of Composite Parts: Structure and Data Acquisition along the Life Cycle

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1. Introduction

Research on digital twins is now more often done in conjunction with the concept of a "digital product passport", that collects information about a component along its whole life cycle. In the case of composite parts, the representation of the part is particularly important, because it needs to support its complicated multi-layer design and must also facilitate the efficient re-use or recycling of parts. Digital twins may thus serve multiple purposes, including the documentation of parts "as manufactured", the assessment of production defects, the determination of the remaining lifetime based on structural health monitoring and the documentation of any repair done to in-service parts. All of these contribute to having a full understanding of the part's properties at the end of its (first) lifecycle and to maximize the value for its second life.

2. Methodology

The structure that is chosen for the digital twin is of high importance to ensure its industrial relevance. It must be compatible with existing design tools and provide an open schema to allow its wide applicability along the lifecycle and over a period of several decades. To fulfill these requirements a schema called "Manufacturing Database" was selected, which was specifically designed for composite parts by Dassault Systèmes and is based on the HDF5 format. It allows the full representation of a composite part, including its 3D design data, lay-up (plybook) and FE simulation results. This database can later be extended with data about the part "as manufactured" (e.g. quality control data), with measurements coming from structural health monitoring systems and with information about any repair done to in-service parts. Through its structure it allows the localized representation of data, e.g. a defect can be assigned to a particular location and layer inside the part.

In order to feed information into the digital twin, technologies have been developed that collect information along the lifecycle of the part. At the production stage, quality control data, such as defects found through visual inspection, ultrasonic testing or X-Ray can be inserted into the digital twin at the exact location inside the parts. Similarly, structural health monitoring systems that acquire information about defects that occur during the in-service lifetime offer the ability to represent e.g. emerging cracks or impact damage. Again, these defects can be localized and represented in the right position to enable an estimation of the remaining lifetime of the part.

Finally, when parts need repair, the repaired area, the materials used and the process parameters applied can be included in the digital twin. Given that such repair work is often done manually, novel methods have to be used that allow the 6D tracking of tools relative to the part's coordinate system. This enables the direct transfer of the repair information into the 3D model of the part, without the need for much manual interaction.



Figure 1. *Visualization of the data structure (left), setup or repair tool with 6D tracking.*

3. Results / Conclusions

The structure of the digital twin was implemented in software (see figure 1; left) and interfaces were defined to all process steps along the lifecycle of the part, most notably to quality control, structural health monitoring and repair (figure 1; right). It could be shown that all processes allow the proper representation of the data in the 3D coordinate system of the part and that the data structure of the digital twin could be easily extended to include e.g. more complex data coming from quality control systems. Furthermore, the digital twin was found suitable to perform FE analysis aiming at calculating the remaining margin of safety in the presence of deviations during production or of the remaining lifetime based on signals coming from structural health monitoring systems.

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Composing Digital Product Passports to Support Remanufacturing in Aviation

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1. Introduction / Objectives

Information about defects, rework, or repair performed over the lifetime of an aircraft can help increase the efficiency of aircraft recycling and remanufacturing at end-of-life (EoL), the overall goal being to enable useful recovery of about 30% of sheet metal parts and thermoplastic fibre-reinforced composite panels. These remanufacturing processes are supported by a set of digital tools that build upon a digital product passport (DPP). The tools facilitate efficient dismantling processes to extract usable sheets or panels from an aircraft. In the presentation and paper, we detail the development of a so-called DPP Composer

that helps individual aviation partners such as original equipment manufacturers (OEMs), operators, and maintenance, repair, and overhaul organizations (MROs) to define the datapoints needed to support aircraft remanufacturing. We discuss the various pitfalls and lessons learned during this process, including aspects related to ensuring mutual trust, securing data (file) exchanges, and protecting partners' intellectual property (IP).

2. Methodology

In the aerospace industry, only components with a remaining lifetime or a written recertification process by the OEM are adequately re-used as spare parts. The vast majority of the structural material (aluminium alloys) is shredded without separation and loses 90% of its value due to incompatible compositions when recycled. In the future, the situation will be aggravated as more and more planes and components made out of carbon and glass fibre composite materials will reach their end of life. Currently, 98% of these materials end up in landfills.

The EU COMPASS project establishes a remanufacturing process that reuses end-of-life components at the level of sheet metal and composite panels rather than converting them back to raw material and/or landfilling. This is achieved through (thermo-)forming processes that allow the re-shaping of parts and components to give them a second life.

To facilitate the remanufacturing process, data about the aircraft fuselage and wings (and their repair histories) are needed. These are collected along the whole operations and maintenance lifecycle, and stored in a digital product passport (DPP). The DPP is part of a DPP management system designed to manage access, storage, and updates of data over a period of 20 to 30 years involving all actors along the entire, circular lifecycle of an aircraft structure.

NLR contributed, from aerospace perspective, to the design and implementation of a supporting platform – the so-called *DPP Composer* (Figure 18) – for the collaborative definition of datapoints to be securely shared between the actors along the lifecycle of an aircraft. We started by collecting stakeholder user stories and needs related to registering, storing, and retrieving data files in various formats, to and from the DPP management system, using interfaces tailored to remanufacturing in aviation. The DPP Composer, which turned out to be a valuable component of the DPP management system, was evaluated by the project partners who partly represent the actors along the of an aircraft structure's lifecycle.



(a) (b)

Figure 18. (a) Digitalized aircraft component as visualized in the AR Dismantling Assistant developed by COMPASS partner AIT and (b) associated data points within the DPP Composer developed by NLR

3. Results / Conclusions

Collective collaboration between various industry partners is always a challenge, due to information technology (IT) barriers such as firewalls and secured file sharing and storage, and operations technology (OT) factors such as unique ways of working and independent enterprise resource planning (ERP) tools, as well as aspects such as trade secrets and intellectual property (IP). It is therefore necessary to carefully plan which datapoints are to be shared with whom, based on data sovereignty issues such as controlled access based on organization, role, and purpose. For industry partners with less digitalization experience, producing a DPP can be a daunting challenge. With the help of tools like NLR's DPP Composer, it becomes easy for OEMs, MROs, and flight operators to better understand and manage their dataflows into and out of the DPP, facilitating the level of information exchange required to support remanufacturing ambitions within the aviation industry.

Acknowledgement: The COMPASS Project is funded by the European Commission within the Horizon Europe Programme, grant number 101136940. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Circular recycling of thermoplastic composite laminates

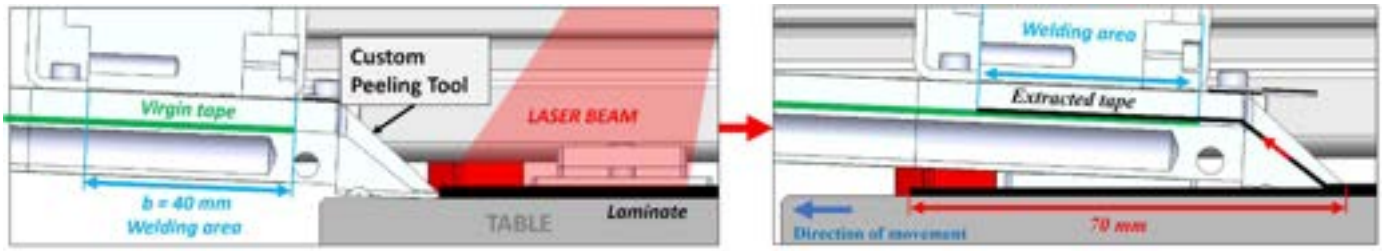
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1. Introduction / Objectives

Achieving circularity in aerospace-grade thermoplastic composite structures requires recycling technologies that preserve both carbon-fibre performance and the functional architecture of unidirectional UD tapes. Current recycling routes for carbon-fibre-reinforced thermoplastics, including mechanical comminution, thermal recovery and chemical matrix removal, typically lead to fibre shortening, loss of tape morphology or separation of fibre and matrix, thereby limiting closed-loop reuse of high-value CF/PEEK materials.
This work presents a structure-preserving recycling route for CF/PEEK UD tapes recovered from consolidated automated fibre placement (AFP) laminates within the EU-funded "CompSTLar" research project. The objective is to selectively separate individual tapes while maintaining matrix distribution, fibre continuity and orientation. The innovation lies in targeting reuse in thermoplastic AFP process chains, where tape geometry, consolidation quality and defect control are decisive for laminate performance. The approach therefore addresses a key limitation of current recycling strategies by avoiding the conversion of endless fibres into short-fibre or isotropic recyclates.

2. Methodology

The investigated recycling route is based on controlled interlaminar deconsolidation of CF/PEEK laminates. In contrast to conventional recycling routes, which generate discontinuous material streams or separated fibre and matrix fractions, the process aims to recover individual UD tape segments while preserving the intrinsic tape structure. Localized and precisely controlled heat is applied to the tape-to-tape interface. The thermal input reduces interlaminar bonding sufficiently for tape extraction while avoiding full remelting of the tape cross-section and minimizing fibre distortion.
A custom-designed peeling tool, retrofitted into a laser-powered AFP machine, is used to initiate and propagate ply separation and tape extraction. The tool geometry and process kinematics are designed to introduce shear-dominated loading at the tape-to-substrate interface, thereby reducing bending-induced damage and limiting the risk of fibre breakage. Key process variables include interface temperature, peeling speed and tool angle. Their influence on tape integrity is assessed through visual inspection, optical microscopy and geometric evaluation of the tape quality. Microscopy-based evaluation is particularly relevant because thermoplastic UD tapes may contain defects such as voids, thickness variations, fibre-angle deviations and interlaminar imperfections.



To restore compatibility with continuous AFP processing, the recovered tape segments are joined by an in-line welding step. The hot-disk welding process relies on controlled surface remelting of the PEEK matrix and axial alignment of adjacent tape segments under defined temperature and pressure conditions. Process monitoring is implemented to ensure reproducible thermal input and to avoid excessive matrix squeeze-out, local overheating or fibre waviness.
The recovered and welded tapes are evaluated with respect to geometry, surface quality, impregnation state and mechanical performance and requalified in AFP trials using the processing window derived from virgin CF/PEEK reference tapes. Characterization includes short-beam shear testing, tensile testing of reprocessed laminates, microscopy-based void and interface assessment, and comparison with virgin reference material.

Figure 1. *Schematic representation of the start procedure for this structure-preserving recycling route, including localized interlaminar deconsolidation, tape recovery by peeling, preparation for welding tape-segments.*

3. Results / Conclusions

Preliminary investigations indicate that localized deconsolidation combined with shear-dominated peeling can recover CF/PEEK UD tape segments from consolidated AFP laminates while preserving fibre continuity and preferential fibre alignment. This represents a departure from conventional recycling routes, which typically reduce structural composite materials to discontinuous recyclates or separated fibre and matrix streams.
The subsequent welding step enables discontinuous tape segments to be reconnected into a processable tape format based on thermoplastic joining principles. Initial AFP trials are expected to demonstrate that the recycled tape can be placed within the original

thermoplastic processing window and consolidated into secondary laminates without significant loss of stiffness or strength compared with virgin reference material. Since thermoplastic AFP quality is strongly affected by heat input, compaction, void formation, fibre waviness and interlaminar bonding, these aspects are assessed during reprocessing and laminate evaluation. Overall, the proposed route provides a promising pathway for closed-loop recycling of thermoplastic AFP laminates.

Pushing Fibre Reinforced Polymer Inline Inspection Speeds to the Next Level

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[2]Addcomposites Oy

1. Introduction / Objectives

The increasing production rates in aerostructure manufacturing impose stringent requirements on in-line non-destructive testing (NDT), particularly for Automated Fibre Placement (AFP) processes. Current industrial inspection solutions remain largely offline, limiting their ability to ensure process stability and part quality at increasing production rates. At the same time, AFP-induced defects such as gaps, overlaps, and fibre misalignment directly affect structural integrity and certification-critical performance.
This work presents a high-speed, photometric stereo-based inspection system for in-line quality monitoring of carbon fibre reinforced polymer (CFRP) lay-up during AFP. The key contribution is the achievement of inspection speeds up to **1.2 m/s**, enabling compatibility with industrial production throughput.
The system is directly integrated into the AFP lay-up head, allowing immediate, spatially resolved inspection of deposited material. This approach supports the shift towards zero-defect manufacturing and digital quality assurance, which are central objectives in next-generation aerospace production systems.

2. Methodology

The proposed system employs photometric stereo imaging to reconstruct surface normals and detect fine-scale surface deviations associated with AFP lay-up defects. The sensing principle is based on acquiring multiple images under controlled, directional illumination and computing local surface gradients from intensity variations. Feature maps derived from surface normal reconstruction (see Figure 1) are used to enable defect detection and classification. This enables the detection of both geometric discontinuities (e.g., gaps, overlaps) and reflectance-based anomalies (e.g., fibre orientation changes).
A key innovation of this work lies in the system-level integration and optimization for high-speed operation. The sensor is mechanically integrated into the lay-up head of a multi-tow AFP robot, allowing inspection directly after tow placement without interrupting the manufacturing process. To ensure spatial traceability, the system is synchronized with the robot controller via a real-time communication interface, providing position and orientation data for each acquired image frame. To achieve inspection speeds of up to **1.2 m/s**, several system components were optimized, including high-speed image acquisition, high-bandwidth data transfer and buffering, and efficient processing pipelines for near real-time feature extraction. The inspection capability is evaluated using representative AFP defects,

including gaps, overlaps, missing tows, and fibre angle deviations.
Beyond defect detection, the system is designed to enable direct integration of inspection results into a digital representation of the manufactured component. Detected defects, including their spatial position and geometric characteristics, are automatically mapped to the corresponding locations on the part geometry using the synchronized robot pose data and the established sensor-to-robot calibration. This information is subsequently linked to a CAD-based model of the component (e.g., STL representation), allowing the creation of a high-fidelity digital twin or manufacturing database. Within this framework, each detected defect is stored with precise spatial reference and associated metadata, enabling traceability across the manufacturing process chain.
The overall approach is therefore designed with a clear pathway towards industrial deployment, addressing key constraints such as robustness, integration compatibility, scalability, and interoperability within modern aerospace manufacturing environments.

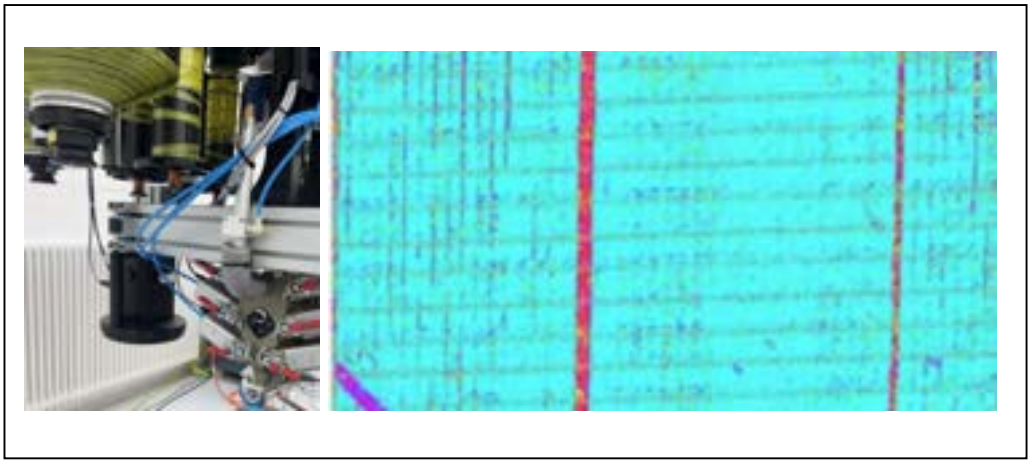


Figure 1. Left: *Sensor mounted behind the lay-up head.* ***Right:*** *Detected feature image showing typical AFP defects.*

3. Results / Conclusions

The developed system demonstrates successful in-line inspection of CFRP lay-up at speeds up to **1.2 m/s**, representing a significant step towards matching inspection capability with industrial AFP production rates. At these speeds, critical defects such as gaps, overlaps, and missing tows remain reliably detectable, confirming the robustness of the photometric stereo approach under dynamic conditions. The integration of the sensor into the AFP lay-up head enables immediate feedback and establishes the basis for closed-loop process monitoring and control. This represents a key advancement towards the implementation of in-situ quality assurance strategies required for certification of high-rate composite manufacturing.
In addition, the detected defects are automatically mapped onto a digital representation of the component, enabling the creation of a spatially resolved digital twin. This allows defect information to be directly linked to the part geometry and stored within a manufacturing

database, supporting traceability, data-driven quality assessment, and the broader digital transformation of aerostructure production.

Acknowledgement: This work was fully funded by the European Union under the project "TOSCA" and the topic HORIZON-CL5-2024-D5-01-08 of the Horizon Europe Framework Programme (HORIZON), grant number 101191394.

Enhanced Surface Defect Segmentation of Carbon Fiber Materials Using Photometric Stereo Imaging

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1. Introduction / Objectives

The high strength-to-weight ratio of carbon fiber materials makes them ideal for aerospace applications. However, their use introduces challenges such as tensile strength degradation due to fiber orientation, layup-induced defects, and material quality variability, necessitating precise inspection methods for structural reliability. Optical inspection methods are increasingly adopted in Tier 1 aerospace suppliers as alternatives to manual inspection; however, their performance is constrained by the highly textured, anisotropic surface, inducing complex reflectance, shadowing, and orientation-dependent optical responses. Additionally, defects such as fiber misalignment and voids exhibit inherently low contrast, while microscopic irregularities remain largely undetectable in conventional 2D vision frameworks.

To address these limitations, we propose (1) an in-house optical sensing system that estimates pixel-level fiber orientation and extracts defect-sensitive features using a photometric stereo-based approach, and (2) an AI-based defect segmentation framework based on a modified SegFormer-B2 architecture, incorporating a custom loss function and low-pass filtering-based preprocessing.

2. Methodology

We propose a two-stage methodology that integrates physics-based optical sensing with deep learning for carbon fiber defect analysis. The objective is to enable robust defect characterization under challenging conditions caused by anisotropic reflectance, low contrast, and complex fiber orientation effects.
First, a photometric stereo-based optical sensing system is developed and mounted on a robotic manipulator. As the manipulator follows a predefined scanning trajectory, multiple images are acquired at each spatial location under varying illumination directions. This controlled multi-illumination setup enables estimation of pixel-level fiber orientation and recovery of reflectance-sensitive information that is not accessible in conventional single-view imaging. From these measurements, five complementary feature modalities are computed, capturing orientation cues and defect-sensitive photometric responses. The resulting feature maps are concatenated into a multi-channel input representation, and a low-pass filtering step is applied to reduce noise and stabilize feature extraction.

The dataset comprises 190 samples of virgin and recycled carbon fiber materials, including gap, missing stitch, and fuzzball defects. A subset of the data is annotated with pixel-level segmentation masks to support dense supervision for learning-based analysis. This dataset will be open sourced available at Zenodo. Previous versions of this dataset for classification are already available for downloads.
In the second stage, a modified SegFormer-B2 model is used as the core analytical framework. The architecture is extended with task-specific prediction heads to support joint defect segmentation and classification (optional), while preserving the transformer-based encoder–decoder backbone (see Fig. 1). A custom multi-task loss function is introduced to balance optimization across objectives and improve sensitivity to small, low-contrast defects and defect contours. The model learns from the multi-channel photometric feature input to produce pixel-wise defect predictions.

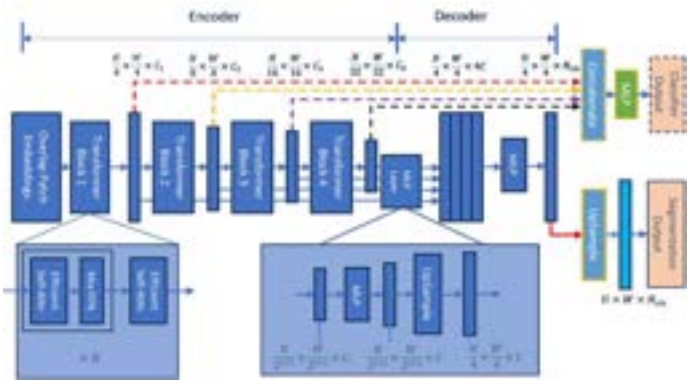


Figure 1. *Illustration of the modified SegFormer B2. The dark blue blocks are the standard SegFormer blocks while the rest of the colored lines and blocks are custom additions to the architecture. The dashed lines and blocks are optional classifier blocks while the solid lines and blocks are the additional segmentation layers.*

Experiments are conducted using PyTorch on an NVIDIA A100 GPU (80 GB). Given the limited dataset size, performance is evaluated using 100-fold cross-validation, supplemented by an 80–20 train–validation split for development and ablation studies. Classification performance is reported using accuracy, while segmentation quality is assessed using mean Intersection over Union (mIoU). The customised model was also benchmarked with the original SegFormer and YOLO 26 architectures and extensive ablation studies were preformed with and without the classifier, loss functions and the input preprocessing, dataset curation etc.

3. Results / Conclusions

Defects including gaps, missing stitches, and fuzzballs were segmented using the proposed modified network. The best-performing configuration achieved an mIoU of 0.65 (Fig. 1), where the architecture incorporates FFT-based low-pass filtering, CutMix augmentation, and a custom contour-preserving loss function. These enhancements improve segmentation quality compared to the standard SegFormer-B2 (mIoU = 0.60) and YOLOv6 (mIoU = 0.28). Representative results are shown in Fig. 2.

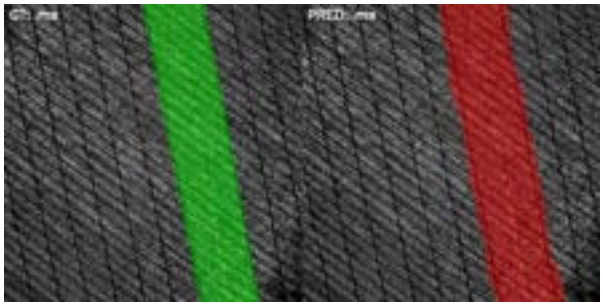


Figure 2. *Illustration of the modified SegFormer B2 output for missing stitch defect. Green region is the ground truth of the defect and red is the predicted defect region by the network*

The objective of identifying the defects in carbon fiber material under anisotropic reflectance, low contrast, and complex fiber orientation effects was successfully performed using the custom developed hardware and the modified SegFormer - B2.

Laser assisted AFP process monitoring towards real-time properties prediction

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1. Introduction / Objectives

CompSTLar project aims at developing advanced digital manufacturing technologies for the production, maintenance, and end-of-life management of next-generation composite aerostructures. Within this framework, special focus is placed on the development of intelligent manufacturing approaches capable of improving process reliability, structural quality, and production efficiency for next-generation thermoplastic composite components. Laser-assisted Automated Fiber Placement (AFP) technologies are being investigated as a promising route for high-rate and out-of-autoclave manufacturing of aerospace structures.

2. Methodology

In this work, a digitalized monitoring framework for laser-assisted AFP processing of carbon fiber reinforced LMPAEK composites is presented towards realtime prediction of laminate mechanical performance. The proposed approach combines in-situ acquisition of process parameters, including nip-point temperature, consolidation force, layup speed, and robot positional data, to generate synchronized and spatially resolved manufacturing datasets during deposition. Process data are continuously acquired and integrated into a digital monitoring environment capable of describing the local thermal and consolidation histories experienced throughout laminate manufacturing, with the aim of having predictive capabilities of expected mechanical properties on real-time.

3. Results / Conclusions

Planar coupons were manufactured and tested following ASTM D3039 standard and were correlated with temperature and pressure maps gathered during manufacturing. Tensile testing performed on ten specimens manufactured under identical AFP input parameters

demonstrated high repeatability, and the associated temperature and consolidation force values revealed highly stable manufacturing conditions throughout the campaign, however minor fluctuations were identified along the planar coupon, that imposes different consolidation conditions in the extracted coupons. The average nip-point temperature showed values in the range of 416 ± 4,19 °C with a clear through-thickness thermal gradient as well as in-plan heterogeneities. Compacting force values were also consistent, averaging between 425.78 ± 5.41 N. Similarly, the deposition speed showed low dispersion (149.67 ± 0,6 mm/s). Mechanical testing (transverse, longitudinal and shear strength), showed consistent values as compared to literature. However, longitudinal testing showed 3 different failure modes (longitudinal splitting gauge middle, lateral gauge top and lateral gauge bottom, see figure 1), ranging from 1.700-2.000 MPa, which will be correlated with the temperature and pressure fluctuations. An experimental campaign is being extended to increase statistics, and to find correlations between process fluctuations, testing outputs and failure modes. This study will pave the way towards a predictive methodology capable of estimating local laminate quality and properties in real time, contributing to smarter manufacturing systems with enhanced process control, reduced inspection requirements, and improved structural reliability for aerospace thermoplastic composites.

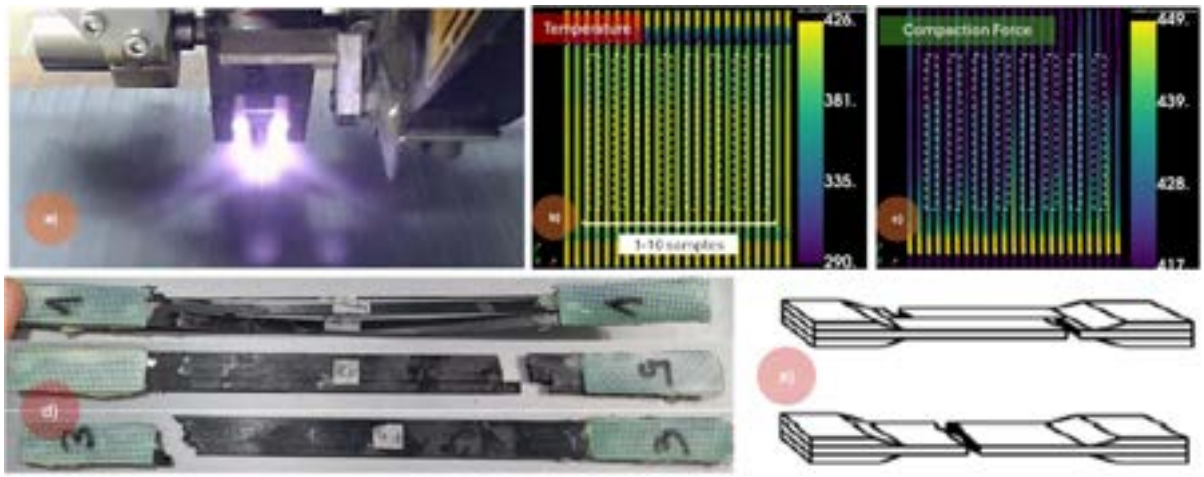


Figure 1. T a) Laser-assisted insitu consolidation of composites by Automated Fiber Placement. b and c) Consolidation temperature and Compaction force digital twins by fusioning monitoring data with robot position. d and e) Longitudinal testing coupons indicating 2 failure modes, as identified in the ASTM D3039.

Leveraging Photonics for the Digitalisation of Composite Manufacturing: The PLEIADES Approach

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1.Introduction

Composite aerostructures require joining and repair routes that reduce mechanical

fastening, improve process repeatability and support circularity across manufacturing and MRO. PLEIADES addresses this need by combining automated induction welding, new vitrimeric composite formulations and embedded photonic sensing into a digitally traceable manufacturing and monitoring framework. The objective is to turn the weld zone from a hidden process region into an instrumented source of quality, process and lifecycle data. The key innovation is the integration of passive, EMI-immune photonic multisensors directly within or near the induction-welded joint, enabling in-process monitoring, weld-quality assessment and later structural-health monitoring. In this way, photonics becomes not only a sensing layer, but a digitalisation enabler for composite manufacturing, repair, rebonding and maintenance workflows.

2.Methodology

The PLEIADES approach is built around three mutually reinforcing technology pillars: automated induction welding with integrated sensing, new benzo-based vitrimer formulations, and interlinked NDT/SHM methodologies. The photonic solution focuses on a multisensor architecture combining integrated photonic circuits with fibre-based sensing on a common optical fibre as shown in **Figure 1**.



Figure 1. *PIC sensor's optical packaging.*

The PIC element is designed to provide local measurements such as temperature, refractive index and pressure, while the fibre sensing element supports strain monitoring. This creates a compact optical sensing chain (**Figure 2**) suitable for harsh composite-processing environments and compatible with single-interrogator readout.



Figure 2. *Fiber connected PIC sensor, and sensor housing*

The sensing architecture is intended for geometry-aware placement in the weld area, including distribution along the weld length and through the joint thickness. By positioning photonic sensors inside or close to the induction weld zone, the system can acquire local information during welding, cooling and subsequent operation of the structure. The same data stream can support process control, in-line quality assurance and longer-term monitoring of

the bonded joint.
The manufacturing methodology links live photonic feedback with induction-welding parameters such as power and travel speed. Weld-related indicators can then be recorded for each part, creating a traceable digital record of process conditions and quality evidence. In parallel, the vitrimer matrix concept supports repair-oriented and circular manufacturing routes, since heat-activated disassembly, rebonding or reshaping can be linked to monitored thermal and mechanical conditions. Data generated by the embedded sensors can therefore feed a wider digital thread connecting process parameters, QA metrics, SHM outputs and MRO decision support. The approach will be explored through PLEIADES demonstrators, including an induction-welded planar dashboard demonstrator with embedded sensors and a wing-related digital-twin framework for ice-detection and de-icing assessment.

3.Results / Conclusions
PLEIADES is expected to demonstrate how embedded photonics can transform induction welding from a largely process-controlled operation into a data-rich, digitally traceable manufacturing route for aerospace composites. The PIC-enhanced sensing concept targets operation across –50 to 400 °C, with reported temperature sensitivity of approximately 70 pm/°C and ±0.15 °C accuracy, refractive-index sensitivity of 2 nm/RIU with ±0.002 RIU accuracy, and a pressure monitoring window of 0.1–1 MPa. These figures support the use of the sensor chain for local thermal, pressure, refractive-index and strain-related monitoring in the weld region. The approach will be assessed through two PLEIADES demonstrators: an induction-welded planar dashboard with embedded sensors and a digital-twin framework for ice-detection and de-icing. Overall, photonics is positioned as the bridge between composite processing, QA, SHM, MRO and circular repair/rebonding workflows.

Acknowledgement: This work was funded from the EU Horizon Europe project PLEIADES, under GA No. 101192721.

Welding of Vitrimer-Based Composites in the TOSCA Project: Influence of Degree of Cure on Joint Performance and Processability

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1. Introduction / Objectives
Vitrimer-based composites are emerging as promising candidates for next-generation aerospace structures due to their combination of thermoset-like mechanical performance and thermoplastic-like reprocessability enabled by dynamic covalent networks. Within the TOSCA project, resistance welding is investigated as a potential joining technology, offering rapid, localized heating and compatibility with automated manufacturing routes. However, its effectiveness strongly depends on the rheological behavior of the vitrimer matrix and its ability to undergo interfacial flow and bond exchange during welding.

2. Methodology
This work reports the first results obtained during the experimental campaign performed within TOSCA regarding the resistance welding of carbon-fiber-reinforced laminates based

on a 3R vitrimer resin system. In the framework of the project, resistance welding is implemented using carbon fiber as the resistive heating element, combined with glass fiber layers providing electrical insulation. The heating element is manufactured as a sandwich structure consisting of carbon fiber prepreg embedded between glass fiber prepreg plies (see Figure 1), all impregnated with the same vitrimer matrix as the laminates to be joined, ensuring chemical compatibility across the system. Within this study, both the adherends and the heating elements were manufactured at different degrees of cure in order to assess their influence on weldability and interfacial performance.
Different curing states were investigated, ranging from fully cured conditions to partially cured configurations corresponding to the so-called "intermediate" and "enduring" stages. The influence of the curing state on weldability was evaluated through a systematic experimental campaign combining process parameter optimization, in-situ thermal characterization during welding, and lap shear strength testing of the resulting joints.



Figure 1. *Roadmap of the heating element's maturation process.*

3. Results / Conclusions

Results show that fully cured laminates exhibit extremely limited interfacial bonding, leading to weak or non-testable joints due to insufficient polymer mobility within the processing window. Improved performance is observed for partially cured materials, with the best results obtained in the lowest cure state ("enduring stage"), where enhanced chain mobility enables improved interfacial contact and higher lap shear strength. However, significant variability in mechanical performance was consistently observed, indicating limited process robustness.
These findings show that, within the TOSCA project, resistance welding of fully cured vitrimer systems is not feasible using the tooling developed and commonly employed for the joining of thermoplastic composites. Consequently, the integration of welding into the manufacturing chain of vitrimer-based aerospace structures requires a redefinition of the material's curing and consolidation strategy.

Evaluating part quality using melt pool signals in a commercial PBF-LB system

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1. Introduction

The complex interplay between processing parameters and resulting part quality in laser-based powder bed fusion (PBF-LB) continues to limit the method's broader industrial adoption. Typical quality challenges, including geometric distortion, inadequate surface finish, balling phenomena, incomplete powder melting, cracking, and keyhole-induced porosity, are strongly influenced by factors such as scan speed, laser power, and melt pool thermal conditions.

Using a commercial two channel PBF melt pool monitoring system, enables determination of temperature profiles generated from instantaneous melt pool radiation measurements. This type of in-situ characterisation adds a source of information for part qualification. While broadly this technique can identify hotter or colder areas during the build, it requires further application, characterization and development in linking these profiles to the specific typical features in PBF-LB produced parts. This work aims to use this type of characterised melt pool monitoring data towards identifying defect features in PBF-LB produced parts as a potential method for non-destructive part quality evaluation.

2. Methodology

Radiative heat transfer arises from the emission of electromagnetic waves, primarily infrared, and is commonly described using the spectral radiance of a blackbody given by Planck's law. Real materials emit less radiation, with emissivity values between 0 and 1, and Ti-6Al-4V melt pools (investigated in this work) pose particular challenges because of their high variable temperatures and emissivity's dependence on wavelength, surface condition and temperature, hinder accurate calibration.
Instead of relying on emissivity-based temperature determination, this work applies a two-colour pyrometry approach using photodiodes with spectral responses of 1070-1400 and 1400-3000 nm, where the ratio of recorded intensities corresponds to integrated spectral radiance over each band. Numerical integration and a bisection method generate a lookup table that converts measured ratios into temperatures. Although differences in emissivity across the two bands are simplified, the method provides qualitative temperature information with potential for assessing part quality.
Secondly, for each PBF-LB/M produced part several terabytes of melt pool monitoring data is produced. Due to the large size and high spatial resolution of the datasets, specialized tools are required for efficient visualization. For this purpose, data pre- and postprocessing, and visualisation strategies are required. In summary this is achieved by merging parts across layers, separation of vectors and contours scans, and subsampling parts to be stored as space efficient parquet files. Thereafter, Potree is used to enable interactive visualization of the large-scale point cloud like data directly in a web browser through efficient streaming and level-of-detail rendering [2]. This enables visualisation of the effect different process

parameters and geometric variations have on the melt pool temperature of parts. An example of this is given in Figure 1 for different geometries investigated.

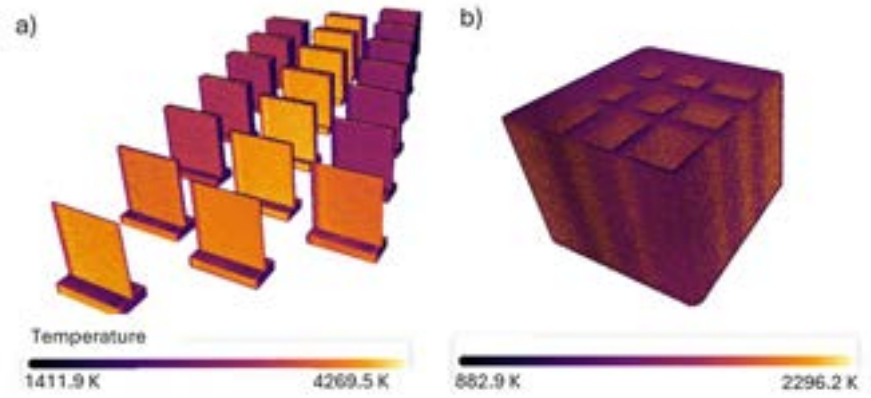


Figure 1. *a) Temperature distribution for walls with varying wall thickness (0.5 – 6 mm) and process parameters. Each row represents a different wall thickness, while each column corresponds to a different parameter set b) Cube with internal cavities*

3. Conclusions

The approach in this work is being developed to the next step to guide targeted metrology investigations, through identifying regions in the melt pool data and visualisations which can be linked to typical quality challenges in PBF-LB/M parts. This requires a selection of data processing techniques linked with advanced metrology (SEM, EBSD & X-ray computed tomography) to highlight part specific focus areas which may contain defects. Furthermore, the possibility of including a twin material model to augment the virtual assessment is being considered.

Overall, linking this type of process monitoring framework as a non-destructive part quality assessment for PBF-LB produced parts could allow for higher acceptance and trust in additively manufactured parts by reducing uncertainties typical of the process and creating a digital quality assessment on a part-by-part basis.

Circular Economy in Space

Chaired by:
Dr. Kai Lindow (Fraunhofer IPK, Germany) & Prof. Miguel Olivares-Mendez (University of Luxembourg, Luxembourg)

Environmental impact of large constellations using the space debris THEMIS indicator

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1. Introduction

Launched and planned large constellations of satellites in low Earth orbit (LEO) are significantly increasing space activity and the number of artificial objects in orbit . They are leading to an increase in the population of space objects, posing a major threat to long-term space sustainability. To address this issue, space debris indicators have been developed to quantify the environmental impact of space missions. However, the interpretation of these metrics at constellation level remains limited in the current state of the art. This work aims to assess the environmental impact of large constellations using the THEMIS debris index. It also provides benchmarks to support the interpretation of the index. The study also introduces a sensitivity analysis to identify the main drivers affecting the index, contributing to a more standardized evaluation of space sustainability. The methodology is presented in Section 2, while results and conclusions are discussed in Section 3.

2. Methodology

In this work, the THEMIS software tool , developed at Politecnico di Milano within a European Space Agency-funded project, is used to quantify the environmental impact of large constellations through a space debris index. The risk index implemented in THEMIS follows the Environmental Consequences of Orbital Breakups (ECOB) approach, evaluating the likelihood and associated effects of breakup events throughout the mission by combining their probability and severity across all mission phases. Since the use of this metric is relatively new, a sensitivity study is performed to analyse the influence of key parameters and to support the interpretation of THEMIS index values, providing reference benchmarks. This analysis focuses on large constellations (i.e., Starlink (US), OneWeb (EU), and Guowang (CN)). It investigates how constellation configurations, orbital parameters, satellite properties, collision avoidance capabilities, and post-mission disposal strategies influence the index. Finally, the environmental impact of large constellations is compared with that of a reference single-satellite mission in a Sun-synchronous orbit (Sentinel-like), selected as a representative LEO case study due to the high density of Earth observation satellites in this orbital region.

3. Conclusions

The results show that the THEMIS index of large constellations is up to two orders of magnitude higher than that of a single satellite in Sun-synchronous orbit (SSO). This highlights their significantly greater impact on the debris environment (Figure 1). However, individual constellation satellites (e.g., OneWeb-like satellites) exhibit lower index values than a typical SSO satellite, mainly due to differences in orbital regime and operational characteristics. The analysis also reveals that the overall impact of constellations is driven by the large number of

spacecraft and replenishment strategies, reflected in the periodic peaks observed in the index over time. These findings emphasise the importance of constellation-level assessment, in view of the increasing number of large constellation deployments.

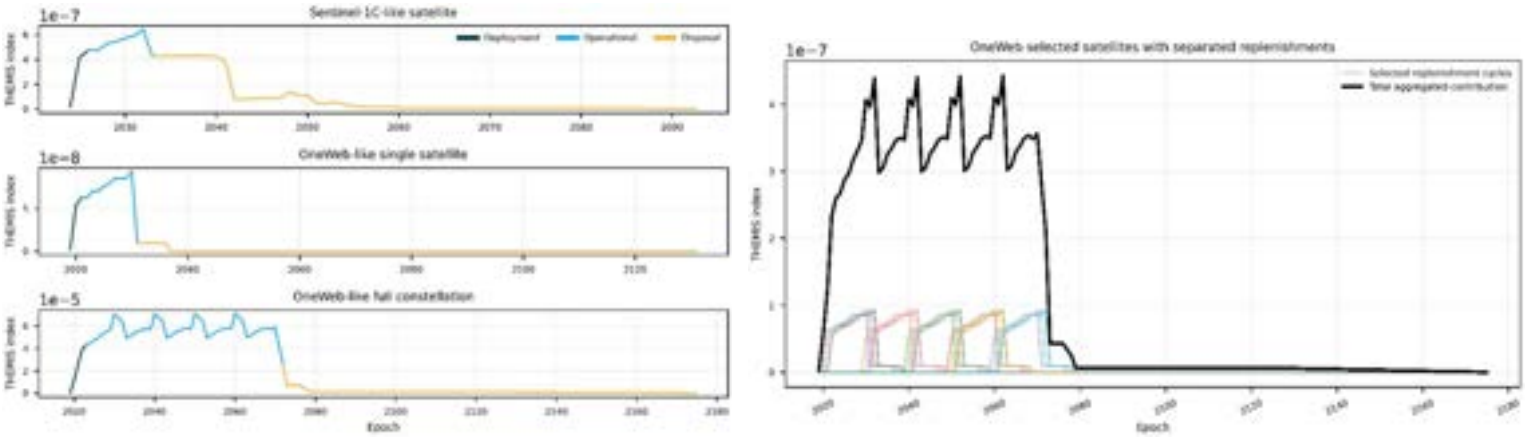


Figure 1. *THEMIS environmental impact evolution for a Sentinel-1C-like satellite, a OneWeb-like satellite, and a full OneWeb-like constellation. Deployment, operational, and disposal phases are highlighted. The right panel shows selected OneWeb-like satellites with separated replenishment cycles and their total aggregated contribution (black curve).*

Acknowledgment: This research received funding from the European Research Council (ERC) under the European Union's Horizon Europe research and innovation program as part of the GREEN SPECIES project (Grant agreement No 101089265). The simulations have been performed using the THEMIS software developed within the European Space Agency contract ESA Contract No. 4000145375/24/D/BL.

A Preliminary Requirements-to-Design Framework for Circular Satellite Systems

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1. Introduction / Objectives

Space sustainability, and especially circularity, is no longer limited to debris mitigation or end-of-life disposal. It is increasingly becoming a design issue that should be considered from the first stages of satellite development. Future satellites may need to support circular actions such as inspection, servicing, repair, reuse, refuelling, component replacement, and controlled disposal. However, these needs are often expressed as broad requirements, without a clear method for linking them to specific satellite design choices from the early design stage, where major system-level decisions are made. This work proposes a preliminary

requirements-to-design framework for circularity-oriented satellite systems, aiming to translate circularity requirements into practical design attributes and early-stage assessment criteria.

2. Methodology

The framework starts by identifying key circularity requirements relevant to satellite systems, including modularity, serviceability, inspectability, removability, refuelling readiness, upgradeability, reuse potential, and end-of-life management. These requirements are then mapped to design features such as standardized interfaces, accessible subsystems, replaceable units, inspection points, modular architecture, and disposal-supporting design provisions.

The next step translates these features into measurable criteria that can be used during early satellite architecture studies. Examples include interface standardization, subsystem accessibility, replacement complexity, inspection readiness, modularity level, and end-of-life demise. A weighted assessment process is then proposed to rank and compare alternative satellite concepts according to mission priorities and circularity objectives.



Figure 19. *Indicative application of the framework to a satellite system*

3. Results / Conclusions

The proposed framework provides an initial structure for connecting circularity requirements with satellite design decisions. It makes circularity easier to consider before the system architecture is fixed and helps identify trade-offs between circularity, technical feasibility, mission performance, and complexity. Overall, the work supports a shift from isolated circular technologies toward a more integrated design logic for future satellite systems.

Toward Circularity in Space: Evaluating and Operationalizing the Circular System Framework for Satellite Reuse

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1. Introduction / Objectives

The Circular Economy (CE) remains conceptually fragmented, with implementations typically optimizing isolated system levels while neglecting cross-level dependencies . Prior work proposed a Circular System (CS) framework to operationalize CE as a multi-level socio-technical system spanning micro (product design), meso (production networks and logistics) and macro (governance and finance) levels, developed through a literature review and demonstrated illustratively through a satellite reuse case . The framework remains conceptual: its constructs have not been validated against practitioner knowledge, and no designer-facing operationalization exists. Multi-level frameworks of this kind require empirical grounding to become actionable.
This research pursues two objectives: (i) to evaluate whether the CS framework's system level constructs are recognized by practitioners as distinct and causally interdependent focus areas of circular transition; and (ii) to operationalize the evaluated framework into a structured set of design criteria and readiness indicators for engineers working toward circularity in space.

2. Methodology

A two-phase qualitative evaluation study is employed to validate the CS framework and evaluate the circularity readiness scaffold proposed in . Phase one and Phase two engage distinct participant groups to avoid consistency bias and strengthen the independence of the evaluation. Phase one comprises semi-structured expert interviews with approximately 20 practitioners from satellite manufacturing, on-orbit servicing, launch services, national space agencies and regulatory bodies, selected through purposive sampling to ensure coverage across all three CS levels . Interview questions are structured around the micro (product design and material choices), meso (infrastructure, supply chain and reverse logistics) and macro (policy, finance and governance) levels of the CS framework. Thematic coding is guided by the CS framework's constructs, with particular attention to cross-level dependencies and points of systemic lock-in identified in . Construct validity is assessed by examining whether practitioners recognize the proposed levels as distinct, real and causally interdependent focus areas of circular transition. Phase two comprises two structured evaluation workshops. The first engages a subset of Phase one participants alongside additional industry practitioners, examining whether the scaffold accurately reflects real-world circular-transition challenges across all three CS levels. The second engages advanced space engineering students at master and doctoral level, evaluating the scaffold's usability and clarity as a design-guidance instrument for engineers approaching circularity in space for the first time. Both workshops employ structured application tasks and reflective debrief protocols consistent with design science evaluation practice to generate evaluative evidence.
The empirical synthesis across both phases generates evaluative evidence on two dimensions: the construct validity of the CS framework as experienced by industry practitioners, and the practical utility of the circularity readiness scaffold as a design-guidance instrument across experience levels. Findings inform targeted refinements to the

scaffold, positioning it as an empirically grounded tool for engineers working toward circularity in space.

3. Results / Conclusions

This study will produce three outputs. First, an empirical evaluation of the CS framework's construct validity, establishing whether its micro, meso and macro levels correspond to how practitioners experience transition requirement for circular in space. Second, a circularity readiness scaffold, a structured set of design criteria and readiness indicators operationalizing the evaluated framework for engineers of space assets, consistent with Bocken et al's identification of a gap between strategic circular intend and concrete product design decisions . Third, a replicable qualitative evaluation approach for CS frameworks in high-technology sectors beyond space.
The broader contribution is how circularity in space can be understood and pursued: decisions at the design, infrastructure and governance levels are causally interdependent, and progress on satellite reuse requires coordinated action across all three rather than optimization of any one in isolation. The study responds to the call in for empirical validation in support of the argument that CE transformation requires system-level alignment.

An Optimization Framework for the Conceptual Design of Hybrid Microsatellite Launch Vehicles with Environmental Assessment

Girolamo Musso, Iara Figueiras, Alain de Souza, Frederico Afonso, Fernando Lau
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1. Introduction / Objectives

The aerospace sector has undergone a profound transformation over the past decades, driven by what is referred to as the New Space paradigm. This shift has fueled increased privatization and a growing demand for dedicated small-lift launch services [1]. Concurrently, environmental concerns have grown, prompting the integration of tools such as Life Cycle Assessment (LCA) within the design phase. Within the New Space Portugal project [2], a design optimization framework for microsatellite launch vehicles is being developed. Driven by simplicity and cost reduction, hybrid rocket motors are investigated as a promising technology for future space launch systems. The targeted mission addresses the launch of microsatellites to a Sun-synchronous orbit from the spaceport under development in the Azores, Portugal. The primary objective of this work is to support early-phase engineering decisions through trade-off studies using optimization techniques that integrate vehicle performance and environmental considerations within a single design framework.

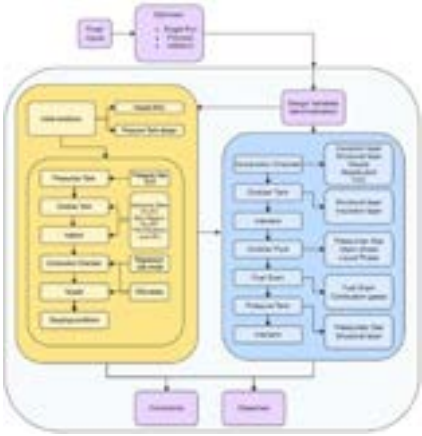


Figure 1. Algorithm workflow.

2. Methodology

Initial efforts resulted in a simplified framework incorporating propulsion, sizing, aerodynamics, flight simulation, and life cycle assessment modules applied to a sounding rocket configuration [3]. Recent developments focused on upgrading the propulsion and sizing routines to enable the modeling and comparison of multiple propellant options and engine architectures through detailed subsystem-level sizing, extending the design space toward orbital-class engines [4]. The considered subsystems are illustrated in Figure 1, where the workflow of the simulation algorithm is presented. Due to the high dimensionality of a complete launch vehicle design problem, the current implementation addresses single-stage configurations, considering all components depicted in Figure 2.

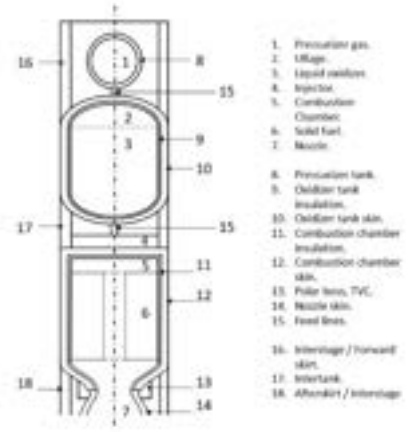


Figure 2. Engine scheme.

The framework incorporates detailed LCA metrics accounting for materials, propellant production, and exhaust emissions, enabling multi-objective optimization studies that trade vehicle performance against environmental impact using EcoInvent and the ESA LCA database [5, 6]. In parallel, the framework extension to support two-stage launch vehicle design through stage-wise decomposition [7] is under development, including preliminary sizing of non-engine subsystems at the overall vehicle level. Preliminary exploration of the design space is performed through comparative studies to assess trends and optimal design choices for hybrid rocket engines, to evaluate their suitability for the proposed mission objective. Multiobjective optimizations are conducted to investigate trade-offs between vehicle performance and environmental impact, aiming to identify Pareto front structures and dominant design drivers across alternative configurations.

3. Results / Conclusions

An optimization framework that supports the preliminary design of a hybrid-propelled launch vehicle while balancing performance and environmental considerations is presented. Preliminary comparative analyses between different propellants and engine architectures suggest promising configurations aligned with the selected design drivers, indicating the potential of hybrid propulsion to achieve the proposed mission objectives with reduced environmental impact. Expected results include Pareto front structures balancing mission performance, expressed in terms of Dv, against environmental impact, assessed through both single-score and category-specific LCA metrics. These trade-off maps will enable systematic comparison across configurations, highlighting dominant design drivers and the suitability of hybrid propulsion for microsatellite launch missions.

Managing Requirements Uncertainty in Early-Phase Spacecraft Design: An Expert-Informed Approach to Design-for-Spacecraft-Reuse

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1. Introduction / Objectives

Spacecraft design decisions made in early phases lock in architectural commitments that determine which lifecycle outcomes remain feasible, including reuse, servicing, and controlled disposal . Design-for-Spacecraft-Reuse (DfSR) extends the Design-for-X tradition to spacecraft circularity, but the requirements that should guide early-phase reuse-oriented design remain uncertain: feasibility depends on orbital regime, infrastructure maturity, and economic incentives, none of which are fully resolved at the time of design . This uncertainty is not a methodological weakness but a structural property of designing for a transitional industrial context.

This paper pursues two objectives: (i) to characterize the sources of requirements uncertainty affecting early-phase spacecraft design for reuse; and (ii) to demonstrate how expert-elicited data can be translated into a regime-conditioned requirements structure that manages this uncertainty before architectural lock-in occurs.

2. Methodology

The study applies a data-driven design research approach combining expert elicitation with Design Science Research (DSR) principles . Sixteen semi-structured expert interviews were conducted with practitioners across satellite manufacturing, on-orbit servicing, launch services, national space agencies, regulatory bodies, and academic research, selected through purposive sampling to ensure coverage of all relevant decision domains in spacecraft reuse.

Interview questions were structured around design feasibility, interface standards, certification pathways, governance, and economics. Data analysis followed an iterative coding process informed by the Gioia methodology , combining open coding for emergent themes, axial coding to group concepts into higher-level categories, and selective coding to consolidate integrative themes into structured design implications. Thematic saturation was reached within the sample.

The analysis identified orbital regime as the primary boundary condition that resolves a substantial portion of early-phase requirements uncertainty: it determines which reuse pathways are technically and economically feasible, which design tracks are appropriate, and which lifecycle strategies are accessible under current and emerging conditions. This insight was operationalized into a two-part design support structure: a regime-conditioned decision architecture that establishes feasibility boundaries across orbital contexts, and a set of four interdependent early-phase design requirements that translate regime-conditioned reuse logic into engineering priorities applicable before design lock-in.

Research quality was addressed through triangulation across expert backgrounds, a documented audit trail of coding decisions, and explicit articulation of boundary conditions to support analytical rather than statistical generalization, consistent with established qualitative quality criteria . The resulting design support structure is grounded in the empirical pattern that requirements uncertainty in spacecraft reuse is not uniformly distributed across design decisions but concentrated in dependencies that orbital regime resolves first.

3. Results / Conclusions

The study produces three outputs. First, an empirical characterization of requirements uncertainty in early-phase spacecraft reuse design, showing that uncertainty is concentrated in regime-dependent feasibility, interface standardization, and certification pathways. Second, a regime-conditioned design support structure demonstrating that expert-elicited data can be translated into actionable early-phase requirements without waiting for full infrastructure maturity. Third, a methodological contribution showing how qualitative expert data can drive structured engineering design decisions under uncertainty.

The broader contribution is a reframing of design-for-spacecraft-reuse as a requirements uncertainty management problem rather than a technology readiness problem. Where infrastructure constrains immediate feasibility, regime-conditioned requirements preserve design optionality, ensuring early architectural decisions do not foreclose pathways that may become viable within the operational lifetime of the spacecraft being designed.

Innovative Electroactive Morphing for disruptive and sustainable wing design

Chaired by:
Dr. Marianna Braza (CNRS, France)

Experimental investigation of the aerodynamic performance increase of an A320 morphing wing prototype in subsonic regime

Abou Khalil J.[1,2,3], Asproulias I.[1], Maynard N.[1,2], Delon X.[1,4], El Akoury R.[1], Harran G.[1], Doll C.[3], Rouchon J-F.[2], Braza M.[1]

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1. Introduction / Objectives

A novel electroactive morphing "live-skin" approach has been developed by the IMFT and LAPLACE laboratories to enhance aerodynamic performance in subsonic and transonic flow regimes. This study concerns the low transonic regime. The system is composed of five rows of piezoelectric actuators, distributed along the suction side from 50% of the chord length to the trailing edge (see Fig. 1). A detailed experimental investigation has been conducted on an Intermediate Scale (IS) A320 wing prototype having a chord of 70 cm and a span of 59 cm in the context of the HORIZON-2023-2027-PATHFINDER- Open Project N° 101129952-BEALIVE-"Bioinspired Electroactive multiscale Aeronautical Live skin", http://horizon-europe-bealive.eu/. The concept is bioinspired by both, the feathers and ailerons of large span hunting birds and the scales of sharks, that provide considerable performance increase. The present study aims at implementing the "live-skin" system on A320 wing prototypes to increase the degrees of freedom of the actuation and drastically enhance the aerodynamic

performance. This multiple DoF actuation capability enables simultaneous manipulation of the vortex dynamics and surrounding turbulence resulting to an optimal fluid-structure interaction system that provides - as demonstrated in the results - *a simultaneous* lift increase, drag reduction, and mitigation of noise sources.

2. Methodology

The A320 IS, "Intermediate Scale" morphing prototype of the BEALIVE project is presented in Figure 1. The experiments are carried out in the S4 subsonic wind tunnel under take-off conditions: angle of attack: 10°, inlet velocity of 21,5 m/sec corresponding to a practically incompressible regime (Mach number of 0.06) and Reynolds number of 1 million. The live-skin system consistes of 5 rows of piezo-ceramic actuators starting from 50% of the chord toward the trailing edge. This location corresponds to an upstream area of the separation point arising near 75% of the chord. This disposal, enhances local momentum along the shear layers thanks to small vortices produced by the actuators vibration that turn in the same direction as existing onces, resulting in lift increase and disrupt through vortex breakdown existing coherent vortices that turn in opposite side. This action, constricts the shear layers through the so-called eddy-blocking effect . This effect results in shear layer thinning and pushes the appearance of von Kármán vortices farther downstream, thus contributing to drag reduction. At the same time, coherent structures rotating in phase with the upper and lower shear layers intensify the Kelvin- Helmholtz vortices, increasing lift. Time-Resolved PIV (TRPIV) operating with a 10kHz of sampling rate has been performed (Fig. 1), The results have been anlysed by Spectral POD that highlights and quantifies the morphing effects on the afore mentioned dynamics and dominant coherent structures. In strong synergy, Hi-Fi simulations have been conducted using the Navier Stokes MultiBlock (NSMB) solver with the Arbitrary Lagrangian-Eulerian (ALE) approach for the grid deformation in respect of the morphing dynamics . The turbulence modelling has been performed through the Organised Eddy Simulation - OES [4,5], sensitized for physical capturing of the coherent structures development due to the mail flow instabilities, (Figure 2).

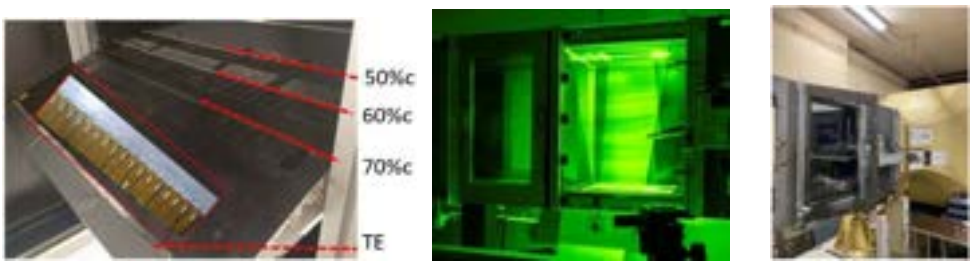


Figure 1. View of the A320 morphing prototype, equipped of the live-skin and piezo-actuators mounted along rows (left). TRPIV set-up in the S4 wind tunnel of IMFT (middle and right).

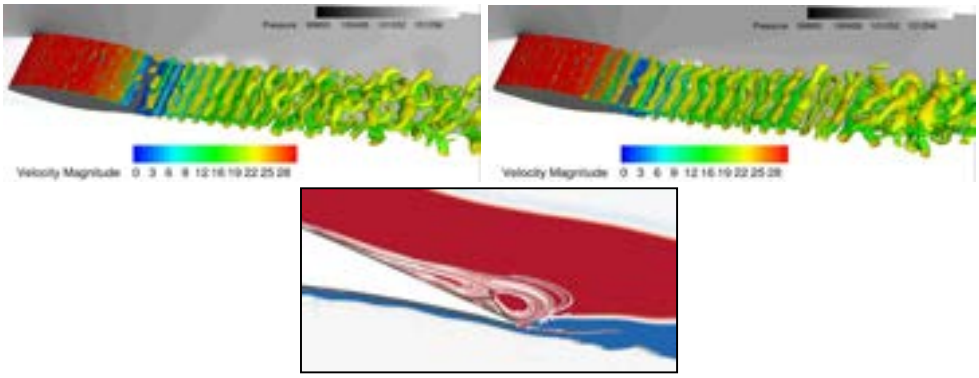


Figure 2. left: Q criterion iso-contours around the A320 wing (static, e.g. non-actuated case), coloured by the spanwise vorticity. Middle: Morphing case: Q criterion iso-contours around the A320 wing (morphing case), coloured by the spanwise vorticity, comparing to the static case, displaying a more regular vortex pattern in respect of the secondary instability where the live-skin has been modeled through Travelling Waves (TW) - left. Right: Streamlines showing the separated area (static case).

3. Results / Conclusions

This study analyses the electroactive "live-skin" morphing effects on an A320 morphing wing prototype having dimensions near half of the real A320 tip area. A considerable increase in lift, up to **4%**, is achieved, accompanied by a **6%** reduction in drag. In specific actuation cases presented at the conference, the aerodynamic efficiency increase reaches an order of **10%.** These performances occur simultaneously with a reduction in aerodynamic noise sources of about **8 dB**. All these values are in close agreement with the numerical simulations. The results obtained in this study confirm the potential of the live-skin morphing concept. In a companion paper of the present session, the concept is also successfully extend on a large-scale A320 morphing prototype of the BEALIVE project, near scale-one. The potential of the live-skin can be extended from laboratory to a wide range of aeronautical applications in aircraft design. In particular, live-skin morphing shows promise for integration into future sustainable and zero-emission aircraft, where efficiency gains and noise reduction are critical.

Aerodynamic performance increase through numerical simulation of a morphing A320 wing prototype in transonic regime

Abou Khalil J.[1,2,3], Asproulias I.[1], Marouf A.[4], Maynard N.[1,2], Delon X.[1,4], El Akoury R.[1], Hoarau Y.[4], Rouchon J-F.[2], Braza M.[1]

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1. Introduction / Objectives

A morphing A320 wing prototype having a 70 cm chord length, an angle of incidence of 1.8°, an upstream Mach number of 0.78 and a Reynolds number of 4.5 million is investigated in respect of a novel morphing approach modelling a "live-skin" through Travelling Waves (TW), in the context of the HORIZON-2023-2027-PATHFINDER- Open Project N° 101129952-BEALIVE-"Bioinspired Electroactive multiscale Aeronautical Live skin", http://horizon-europe-bealive.eu/. The flow regime corresponds to cruise phase of flight. Hi-Fi numerical simulations have been performed with a large range of parameters of the travelling wave (vibration frequency, amplitude, wavelength and actuation area on the suction side). The objective is to find optimal parameter range able to simultaneously increase lift, reduce drag and the transonic buffet as well as to reduce the noise sources.

2. Methodology

This investigation focuses on testing different actuation zones located both upstream and downstream of the shock position to mitigate buffet effects, using a Traveling Wave (TW) approach that model a "live-skin" surface in experiments. The simulations have been carried out by means of the Navier-Stokes Multi Block CFD solver . The grid deformation in respect of the TW has been treated using the Arbitrary Lagrangian-Eulerian (ALE) method in this solver . The OES - Organised Eddy Simulation turbulence modelling approach, able to capture the physical development of coherent structures and their interaction with the chaotic turbulence, has been employed.

This study highlights the significant feedback effect of the near-wake unsteadiness on the Shock-Boundary Layer Interaction (SBLI) region and *further upstream*. The morphing manipulates the downstream unsteadiness producing, thanks to the feedback effect, modification of the dynamics within the shock area and on the overall wall pressure distribution. It has been found that for specific parameter ranges of the TW, the shock "excursion due to the buffet is considerably attenuated, as well as the shear layer Kelvin-Helmholtz and von Kármán vortices (fig. 1). A large parametric study has been performed in respect of wavelength (λ), vibration frequency (f), amplitude (a) and application zone . Particular attention is paid to configurations where the actuation zone beginsn upstream or overlapping the shock region (Figure 1, middle) to directly influence the separation bubble under the shock foot and the near-wake dynamics that have a strong influence on the upstream of the SBLI dynamics.



Figure 1. *left: Turbulence structure around the A320 morphing wing: Q-criterion contours coloured with velocity magnitude and density gradients displayed at the symmetry plane shows the formation of Kelvin-Helmholtz (KH) vortices and the von Kármán vortices during the buffet cycle together with chaotic turbulent vortices. The unsteadiness in the near wake region highly influences the upstream area. This 3D simulation clearly visualizes the development of the secondary instability (undulation of the vortex rows in the spanwise direction) and the appearance of secondary shocks at each crest of the 3D coherent vortices undulation streamwisely and spanwisely. Middle: Visualization of the maximum upstream and downstream positions of the shock wave in the*

static (non-actuated) case, located between x/c = 0.66 and x/c = 0.72. The green area (dashed vertical lines) corresponds to an optimal actuation zone indicated on the right. Right – Schematic representation of the various travelling wave (TW) actuation zones tested in the continuation study, covering regions upstream of the shock as well as zones that extend across and beyond the shock excursion envelope.

3. Results / Conclusions

This study identified an optimal actuation area and TW parameters using λ = 3 and λ = 6 cm, f = 750 Hz and a low actuation amplitude of 0.3 mm in the green zone (from x/c = 0.514 to x/c = 0.686), which led to a simultaneous lift increase and drag reduction of (+0.85%) and (−2.3%), respectively, as well as to an increased aerodynamic efficiency (Cl/Cd) of +2.65%. Moreover, a 91.7% lift *rms decrease has been obtained,* corresponding to a practically total mitigation of the transonic buffet, (Figure 2). For a specific actuation range, from x/c = 0.69 to x/c = 0.99 using λ = 6 cm, f = 250 Hz and a low actuation amplitude of 0.3 mm a drag reduction in the order of 6,5% has been obtained, as well as a lift-to-drag ratio increase of 2 %. These facts are obtained thanks to a downstream shift and weakening of the shock accompanied by a significant attenuation of the spectral energy in the wake, indicating reduced generation of trailing edge noise.

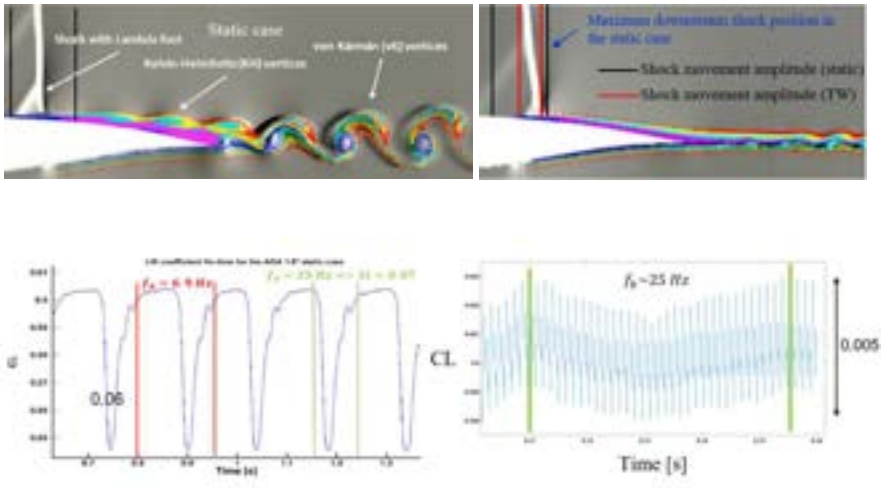


Figure 2. *Left (Static case): Top - The development of Kelvin–Helmholtz (KH) and Von Kármán (VK) vortices leads to a thick wake and induces upstream shock motion. Bottom - Corresponding lift coefficient signal, showing large oscillations with an amplitude of 0.06. Right (Travelling Wave case): Top – Suppression of shear layer instabilities is convecting VK vortices farther downstream, thus reducing the wake thickness and significantly decreasing the shock motion amplitude (difference between red (morphing) and black (static) vertical lines). Bottom – Corresponding lift coefficient signal, with a reduced rms, consistent with the stabilized flow observed above.*

Numerical study of travelling and standing wave morphing on an A320 wing prototype in subsonic regime at Reynolds number of 1 million

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1. Introduction / Objectives

This study investigates the morphing effects on the "Intermediate Scale" (IS) Airbus A320 morphing wing prototype of the HORIZON-2023-2027-PATHFINDER, Project N°101129952-BEALIVE, "Bioinspired Electroactive multiscale Aeronautical Live skin", http://horizon-europe-bealive.eu/ by means of Hi-Fi numerical simulation. A novel "live-skin" morphing concept of the present project has been modeled in this study through Travelling Waves (TW) and Standing Waves (SW) actuation. The waves model the live-skin actuation with the same vibration, amplitude, wavelength and actuation area parameters as in the experimental studies of this project, where the live-skin is constructed through a high DoF of piezo-ceramic actuators disposed along strategic areas of the wing's suction side. Applied in selected regions of the wing, these waves have the objective, (as will be seen in the present study), to modify the separated shear layers and the near wake vortex structures due to main instabilities, thus increasing the aerodynamic performance and reducing noise sources in specific optimal parametric ranges. The present work aims identifies and analyses the coherent structures and main instability modes modification due to the morphing, by means of Proper Orthogonal Decomposition (POD) and Spectral POD (SPOD).

2. Methodology

The flow is analysed around the 70 cm-chord Intermediate Scale "IS" Airbus A320 morphing prototype of the BEALIVE project, operating in a low subsonic regime corresponding to take-off conditions, with an upstream velocity of 21,5 m/sec (corresponding to a low Mach number of 0.063), an inlet velocity of 21.5 m/s, a Reynolds number of 1×10^6 and an angle of attack of 10°. The morphing effects are modelled by means of surface travelling waves and standing waves applied on the wing's suction side.
Four key parameters are considered: wavelength, frequency, amplitude, and the actuation zone length and position on the extrados. A large parametric study is therefore conducted by varying these morphing parameters in order to identify favourable configurations and to compare the aerodynamic response of TW and SW actuation with respect to the static non-actuated case, Figure 1. High-Fidelity numerical simulations are conducted by means of the Navier–Stokes Multi-Block (NSMB) solver . The mesh deformation is performed through the Arbitrary Lagrangian–Eulerian (ALE) method , allowing the wave actuation to be imposed on the wing surface. The turbulence modelling approach used is the Organised Eddy Simulation (OES) , sensitised for capturing the physically correct coherent structures development due to the amplification of main flow instabilities. POD and SPOD are applied to extract, analyse and compare the coherent structures and their shedding frequencies in static (unactuated) and morphing cases. These modal decomposition techniques reveal the modification of the dominant energetic coherent structures due to the morphing, Figure 2. Particular attention is

paid to the shear-layer dynamics, the wake organisation, the von Kármán and its subharmonic modes, as well as the Kelvin-Helmholtz frequencies, strongly related to the modal content changes and to the aerodynamic performance, Figure 3.

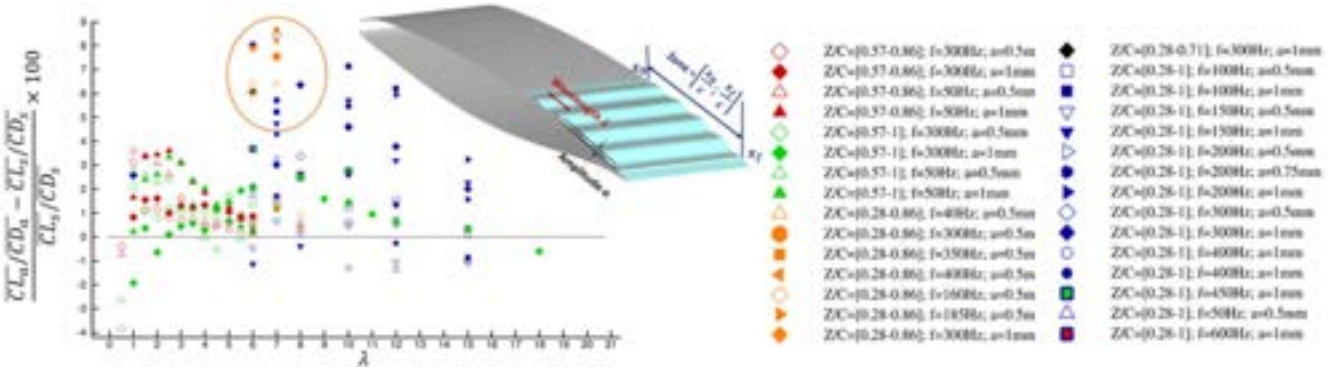


Figure 1. *Relative variation of lift-to-drag ratio for different sets of TW actuation parameters with respect to non-actuated case.*

3. Results / Conclusions

The present morphing actuation introduces an eddy-blocking effect in the shear layers, injecting small-scale vortices that, in optimal cases, they constrict the shear layers thanks to an eddy-blocking effect , that significantly reduces the wake width and delays the development of the von Kármán instability, swept farther downstream. These facts result in measurable aerodynamic benefits, including drag reductions up to **8%** and increases in aerodynamic efficiency in the order of **8%**, (Figure 1). Moreover, the parametric study reveals that actuation applied upstream of the natural separation point yields a higher performance increase than actuation zones overlapping the separation region, underlining the critical importance of actuation placement in morphing wing design. POD and SPOD show that the morphing modifies the dominant energetic coherent structures of the wake, Figures 2 and 3, confirming the ability of the live-skin concept to increase the organised character of the present turbulent flow by reducing the effect of harmful instabilities.

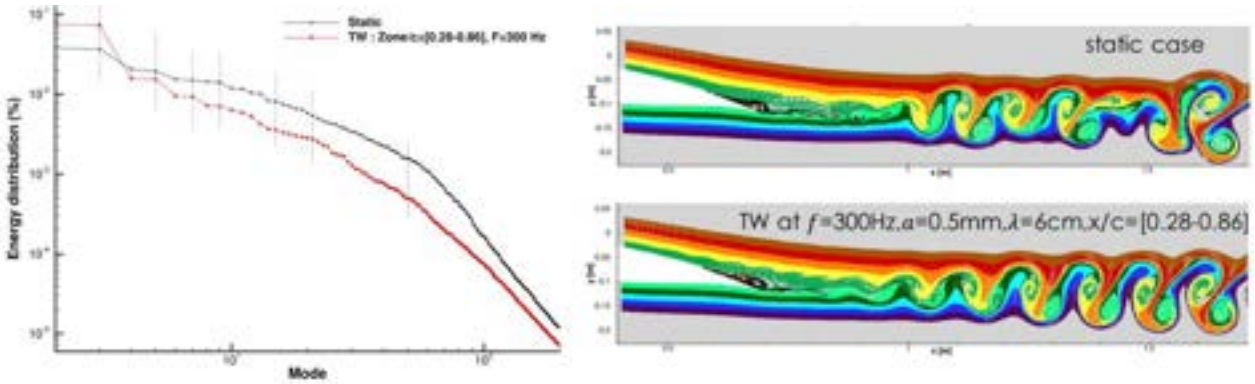


Figure 2. *Left: Energy distribution of the POD modes, comparing the static case to the TW morphing case with actuation frequency f=300 Hz, a=0.5mm, λ=6cm, X/c=[0.28-0.86]. Vertical lines show the slopes changes towards more turbulent statistical content. Mode 1 corresponding to the mean field has been removed to show the fluctuating energy distribution only. Right: Streaklines visualisation of the reconstructed fields from the first most energetic POD modes. The colour of each particle represents its initial position. In the morphing case, a drag reduction of 7.86% is obtained, associated to a lift-to-drag ratio increase of 8.67%.*

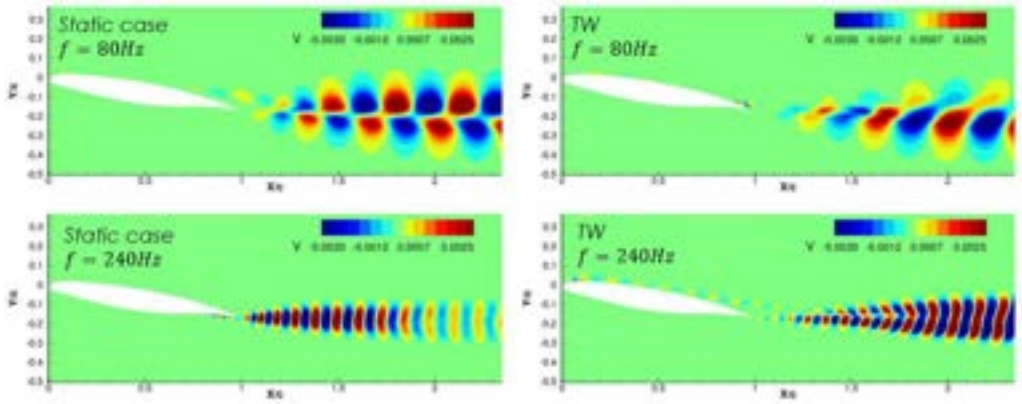


Figure 3. *SPOD shape modes, comparing the vertical velocity component fields at the predominant frequencies $f = 80Hz$ (Top) and $f = 240\ Hz$ (Bottom). Left: static case, right TW morphing with actuation frequency f=300 Hz, a=0.5mm, λ=6cm, X/c=[0.28-0.86].*

Numerical analysis of embedded actuators effects on an A320 morphing wing prototype for aerodynamic performance enhancement

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1. Introduction / Objectives

The aviation sector faces increasing pressure to reduce fuel consumption and emissions while maintaining high aerodynamic performance during take-off and landing. Within the HORIZON-2023-2027-PATHFINDER-Open-Project N°101129952-BEALIVE-"Bioinspired Electroactive multiscale Aeronautical Live skin", (http://smartwing.org/bealive/EU/), this work investigates a bioinspired "live-skin" concept based on distributed electroactive morphing actuators for active flow control. The baseline configuration considered in this study is an intermediate-scale (IS) A320 airfoil having a chord of 70 cm and morphing actuators embedded near the trailing edge, designed to interact with the turbulent boundary layer and near wake through controlled oscillatory motion, enabling manipulation of coherent flow structures and aerodynamic performance enhancement. Moreover, the study is currently being extended to a large-scale (LS) wing–flap configuration having a chord of

2.40 m, where the actuators are relocated onto the flap element to increase their effectiveness in separated and unsteady flow regions. The following methodology and results refer to the IS A320 airfoil.

2. Methodology

High-fidelity numerical simulations have been performed using the NSMB (Navier–Stokes Multi-Block) CFD solver to investigate the aerodynamic effects of electroactive morphing actuators integrated into a A320 wing prototype. The simulations were carried out under low-subsonic conditions at a Reynolds number of 1×10^6, a Mach number of 0.06, and an angle of attack of 10°, representative of high-lift operating conditions. Three morphing actuators are embedded on the suction side of the airfoil near the trailing-edge region, at the source of flow separation and wake instabilities. The actuator motion was modeled through prescribed sinusoidal oscillations with tunable frequencies and amplitudes representative of the experimental electroactive devices developed within the BEALIVE project. To accurately capture the moving boundaries induced by the actuator deformation, the Arbitrary Lagrangian–Eulerian (ALE) formulation was employed , allowing the structured computational mesh to dynamically adapt to the actuator displacement while preserving mesh quality. The low-subsonic flow regime was solved using the Weiss–Smith preconditioning technique to improve convergence and numerical stability. The simulations were conducted using an unsteady dual-stepping approach with a time-step of 10^{-5} s to resolve the vortex shedding mechanisms and the actuator-induced coherent structures. Turbulence effects were modeled using the Organised Eddy Simulation (OES) approach , which is particularly suited for resolving large-scale coherent flow structures generated by active flow control devices. The methodology focused on analyzing the coupling between actuator kinematics, boundary-layer behaviour, and wake dynamics. Time-averaged and instantaneous aerodynamic quantities, including lift and drag coefficients, were evaluated and compared with the non-actuated configuration. In addition, vortex dynamics and flow topology were examined through vorticity and velocity-field analyses to identify the physical mechanisms responsible for aerodynamic performance improvements.

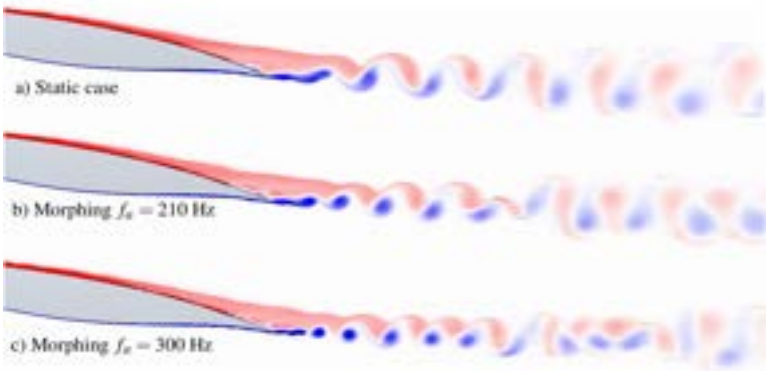


Figure 1. *Instantaneous vorticity contours in the near wake of the intermediate-scale A320 airfoil for the static (non-actuated) case and two actuated cases.*

3. Results / Conclusions

The present study investigated the effect of embedded morphing actuators on an intermediate-scale (IS) A320 airfoil under take-off and landing conditions using high-fidelity unsteady CFD simulations. It shows that the present morphing concept significantly alters the wake topology and boundary-layer development. Instantaneous flow fields reveal the generation of coherent vortical structures induced by the actuator motion, which interact with the natural shear layer and delay the roll-up of large von Kármán vortices (Fig. 1). Time-averaged results indicate a reduction of the mean recirculation region, a thinner wake, and a decreased velocity deficit compared to the non-actuated case. These modifications are associated with a re-energization of the suction-side boundary layer near the trailing edge, leading to delayed separation and improved pressure distribution. A morphing frequency of 180 Hz increases the time-averaged aerodynamic efficiency by 6% compared to the non-actuated case. Building on these findings, ongoing simulations are currently extending the analysis to a wing–flap configuration with actuators located on the flap element. The corresponding results will enable a direct assessment of the scalability of the live-skin morphing towards real scale regarding the aerodynamic performance increase.

Experimental and numerical study of a morphing a high-lift wing-flap configuration through a system of actuators forming a “live-skin”.

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1. Introduction / Objectives

This study investigates experimentally and numerically the effect of a novel electroactive morphing concept based on a “live-skin”, composed of a significant number of piezo-actuators able to deform and vibrate with optimal frequencies, amplitudes and wavelengths. This “skin” forms a streamwise travelling wave (TW) actuation and is disposed along strategic areas of the lifting structure’s suction side. This new morphing approach has been experimentally implemented on the “Large Scale” (LS) high-lift A320 morphing prototype having a chord of 2.40m and a span of 2m, in the context of the HORIZON-2023-2027-PATHFINDER Project N° 101129952-BEALIVE-"Bioinspired Electroactive multiscale Aeronautical Live skin”. The experiments have been conducted in the S1 wind tunnel of the IMFT regarding the take-off flight phase in low subsonic regime at 2° of incidence, Reynolds number of 2.25 million and a Mach number of 0.037 is studied. The total chord of the LS prototype in “clean” is of 2.40 m and of 2.70 m in take-off. The simulations provided the modification of the near wake structure thanks to the morphing, as well as the impact on the main turbulence quantities, turbulence stresses and kinetic energy.

2. Methodology

In this study, the experimental campaign was carried out at a Reynolds number of 2.25 million corresponding to an upstream velocity of 12.5 m/s. To enable the determination of the pressure coefficient C_p along the whole configuration, a dense array of LMI ("Low Measurement Indicator") pressure sensors was applied on the middle spanwise section of the LS prototype. These sensors are defined by their low-pressure range, down to 6 Pa as positive or negative increment, making them suitable for aerodynamic measurements. Moreover, a MEGGITT unsteady pressure transducer has been located at 77 % of the flap's chord on its suction side. The sampling frequency of the MEGGITT is about 6000 Hz. This transducer is coupled with an analog filtering unit designed to suppress high-frequency electrical noise and eliminate interferences produced within wind tunnel environment

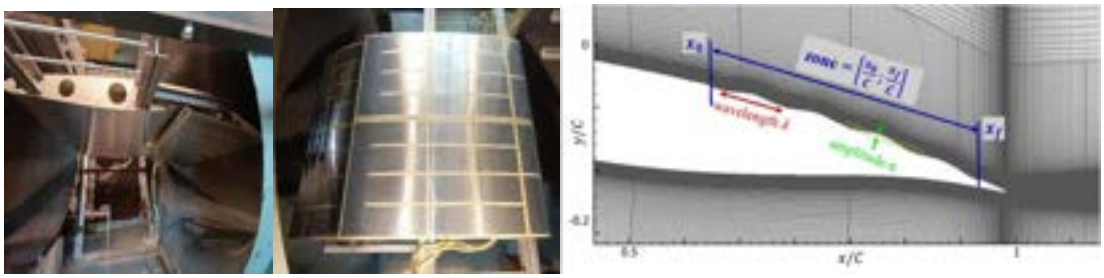


***Figure 1**. Large-Scale (LS) A320 prototype composed of a fixed-part and of a high-lift flap having a total chord in take-off of 2.70 m and a span of 2m in the S1 wind tunnel of IMFT (left). Schematic representation of the live-skin modelling through a Travelling Wave (TW) implemented on the suction side of the high-lift flap according to eq. (1).*

The simulated domain and the computational mesh of $734{,}050$ elements leading to an y^+ value $\ll 1$, have been chosen based on previous convergence studies carried out in the SMS European project . In addition, the present mesh has been refined near the actuated zone. The mesh deformation has been considered through the Arbitrary Lagrangian Eulerian (ALE) approach . The simulations were conducted with NSMB solver . The "live-skin" morphing has been modelled as a deformation of the suction side surface according to a Travelling Wave (TW) whose parameters are the same as for the "live-skin" actuation. The TW is defined as a sinusoidal deformation with specific smoothing at the beginning and at the end of the implementation zone as detailed in Eq. 1:

$$y(x,t) = \begin{cases} \dfrac{x - x_0}{x_1 - x_0} a \sin(kx - \omega t + \Phi) & \text{if} \quad x \in [x_0, x_1] \\ a \sin(kx - \omega t + \Phi) & \text{if} \quad x \in [x_1, x_2] \\ \dfrac{x_f - x}{x_f - x_2} a \sin(kx - \omega t + \Phi) & \text{if} \quad x \in [x_2, x_f] \end{cases} \tag{1}$$

Regarding the turbulence modelling, the Organized Eddy Simulation (OES) approach, has been employed to physically capture the coherent structures development. This approach is based on the ensemble-averaging decomposition of the physical variables in respect of the

turbulence spectrum splitting in one part (the resolved part) regrouping the coherent effects and a second part (to be modelled), regrouping the chaotic effects.

3. Results / Conclusions

The "live-skin" morphing aims at enhancing the interactions between the solid structure's actuated zone and the fluid, thus affecting the different shear layers and their interfaces among them.

Experimental measurements highlight the amplification of the suction at the MEGGITT position of around 9Pa at $Re = 2.25 \times 10^6$ and 17 Pa at $Re = 3 \times 10^6$ when the live-skin is activated at a frequency of 200Hz at 700V.

The main frequencies related to the flow dynamics all around our configuration was analyzed at very specific locations. These monitor points were localized into the different shear layers. The parametric spectrum in frequency was generated based on these frequencies. Ongoing experiments and simulations (Fig. 3) are carried on to identify the aerodynamics forces modification based on the pressure distribution as well as the flow dynamics around the present high-lift configuration.

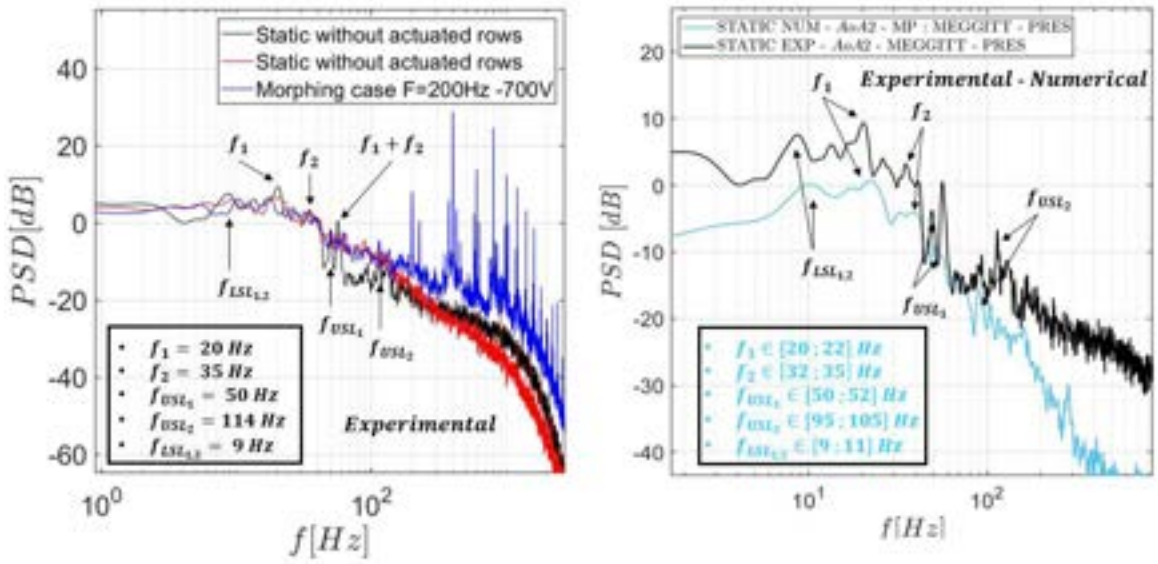


***Figure 2**. Experimental Power Spectral Density (PSD) of the static (no-morphing) configurations compared to the actuated configuration with vibration frequency of 200 Hz at 700V (left). Comparison between numerical and experimental static configurations.*



***Figure 3**. Numerical simulation of the flow around the LS (Large Scale) prototype of the EU - BEALIVE project. Iso-velocity magnitude contours.*

Machine-Learning-based Reduced-Order modelling of a travelling wave morphing system on an A320 wing prototype

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1. Introduction / Objectives

This study is conducted within the European project HORIZON-2023-2027-PATHFINDER, Project N°101129952-BEALIVE, that targets the creation of a bio-inspired electroactive morphing "live-skin" for aeronautical applications. In respect to this concept, the aerodynamic performance of an Airbus A320 morphing wing prototype is studied in a low subsonic regime, at a Reynolds number of 1×10^6 corresponding to an upstream velocity of 21,5 m/s, Mach number 0.063, and an angle of attack of 10°. These parameters are the same as in the experiments of the BEALIVE project presented in a companion contribution. The objective is to create a *Reduced Order Modelling* approach able to handle large parametric sets obtained through the Hi-Fi simulations (and also applicable in the physical experiments of the project) towards future multi-objective optimisation of the morphing parameters. The present morphing is introduced on the suction side through travelling wave surface actuation, representative of a distributed "live-skin" system of piezoelectric actuators used in the experiments. Building on previous promising studies , this actuation aims at improving the aerodynamic performance through coherent structures manipulation that modifies the fluid-structure interaction. The objective of developing a reduced order modelling framework is achieved by means of POD-based interpolation and Machine Learning using a Long-Short Term Memory (LSTM) approach to reconstruct the unsteady flow fields and the aerodynamic coefficients at intermediate actuation conditions in respect of the ones performed, without additional high-fidelity simulations.

2. Methodology

The proposed methodology combines high-fidelity numerical simulations, Proper Orthogonal Decomposition (POD), parametric interpolation, and Long Short-Term Memory (LSTM)

networks to build a reduced order model of the morphing A320 wing. The unsteady flow fields are produced using the Navier-Stokes Multi-Block solver (NSMB) , coupled with an Arbitrary Lagrangian-Eulerian formulation to account for the dynamic grid deformation induced by the morphing surface . The actuation is modelled as a travelling wave deformation applied over selected regions of the suction side. The actuation parameters define the design space, including wavelength, frequency, amplitude, and actuation zone bounds. For each simulated configuration, a snapshot database is constructed by embedding both flow field quantities and grid deformation information. POD is then applied to decompose the Hi-Fi solutions into dominant spatial modes and associated temporal coefficients. This reduced representation captures the main energetic flow structures. The temporal evolution of the POD coefficients is learned using the LSTM networks , allowing the ROM to reproduce nonlinear unsteady dynamics over extended prediction horizons while accounting for the coupled evolution of the flow and mesh motion. To extend the model beyond the simulated cases, a parametric POD interpolation strategy is introduced. POD information is interpolated across the actuation space to reconstruct flow fields and aerodynamic coefficients at unseen actuation frequencies or morphing configurations. The reconstructed solutions are compared with the available Hi-Fi simulations to assess the accuracy of the approach. Fig.1 shows that the error is very low over the field. This framework provides a computationally efficient surrogate model for morphing wing analysis and creates a direct pathway towards optimisation using methods such as Particle Swarm Optimisation or Bayesian optimisation.

3. Results / Conclusions

The reduced order framework accurately reproduces the dominant aerodynamic trends observed in the high-fidelity simulations. The POD reconstruction captures the main time-averaged flow features, while the LSTM prediction preserves the nonlinear temporal behaviour associated with shear layer evolution, vortex formation, and wake dynamics. The predicted aerodynamic coefficients remain consistent with the reference numerical data, demonstrating that the ROM can evaluate the influence of actuation parameters at a significantly reduced computational cost. Overall, the proposed POD-LSTM parametric strategy provides an efficient and physics-consistent tool for exploring morphing wing actuation. By reducing reliance on expensive high-fidelity simulations, it opens the way to rapid optimisation of live-skin morphing concepts and supports the design of adaptive aerodynamic surfaces towards the reduction of fuel consumption and decarbonation of aeronautics.

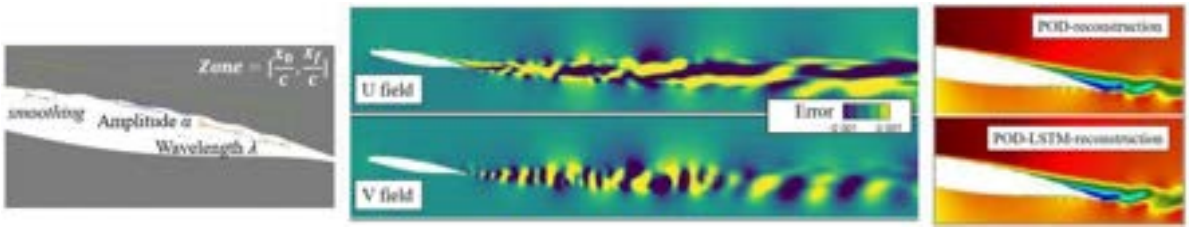


Figure 1: Parameters of the travelling wave. Comparison between classical POD reconstruction and POD-LSTM reconstruction on the prolongated time sequence. Error on the velocity field stays below 0.1%.

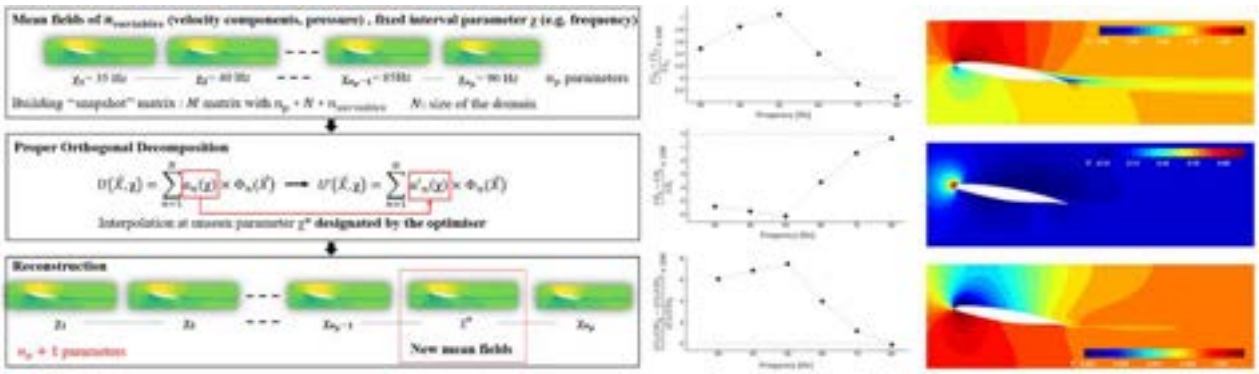


Figure 2: Flowchart of the parametric POD allowing prediction of a new unseen parametric case from a database of Hi-Fi simulations. Actuation database performances ([30-80] Hz, [0.28-0.71]x/c, λ=6cm, a=0.5mm). Reconstructed fields at unseen frequency (55Hz).

Hybrid Electric Regional Fuselage & Empennages (HERFUSE Project)

Chaired by:
Mr. Fabrizio Leone (LEONARDO, Italy)

Innovative Fuselage Structural Concepts for the Integration of Hydrogen Technologies into Regional Aircraft

Ana Sánchez Algarra, Deborah Neumann de la Cruz, María Rodríguez-Montes
Airbus Defence and Space

1. Introduction / Objectives

The goal of this study is to design a fuselage that contributes to the replacement of a regional civil aircraft mission of 80 pax / 500 NM with a hybrid mission using liquid hydrogen and SAF. Our study will focus on studying the solutions and impacts of the installation of innovative technologies on conventional fuselages of turboprop aircraft.
The Clean Aviation Joint Undertaking's Strategic Research and Innovation Agenda (SRIA) aims to replace up to 75% of the world's civil aviation fleet by 2050 with sustainable aircraft technologies. For turboprop aircraft, the overall objective of the SRIA is to achieve a 50% decrease in emissions by 2050 (90% including SAF). One of the most impacted aircraft components in this agenda is the fuselage, which is the object of our study. For the first 50% of CO2 reduction, we will introduce the LH2 systems, and the use of full SAF + LH2 will lead to 90% fuel reduction.

2. Methodology

The main driver to contribute to the SRIA emissions objectives, in this study, is to design a fuselage and empennage structure that is 8% lighter than the state of the art components,

including installation effects of the hybrid-electric propulsion system.
The study will be performed in several steps:

- Preliminary analysis: estimations of fuel needed for the mission, fuselage weight breakdown estimation, analysis of the space allocation model (figure 1), in order to optimize the system's distribution in the fuselage structure.
- Detailed fuselage structural design: trade-off of systems location in the aircraft, definition of the structural adaptations needed for the new equipment, integration of new generation materials in order to obtain weight and emissions reduction, interfaces integration, and feasibility analysis of the innovative structures. Regarding the integration of aircraft systems into the fuselage structure, we will perform an analysis of the maintainability and operational requirements of liquid hydrogen fuel tanks ([1]), in order to evaluate the integration of tank extraction solutions into the aircraft fuselage, e.g. aircraft doors or ramps. With the aim of providing a high power density and high efficiency fuel cell solution, the integration of different fuel cell alternatives into the aircraft will be investigated ([2]).
- Lifecycle assessment: a screening LCA is also performed to study the potential environmental impacts of the proposed fuselage compared to its state of the art. The assessment aims to reflect impact reduction of reducing structural weight and to assess the changes of using a full metallic-based frame to mixing it with composite materials.



Figure 1. *Structural design proposal of innovative fuselage*

3. Results / Conclusions

For the fuselage and empennage to contribute fully to the 50% technologically-based emissions reduction with respect to the reference mission, the structural weight needs to be reduced 8%, in order to contribute a total 5% to the emissions reduction. The remaining contributions correspond to other airframe and systems improvements. The fuselage + empennage contribution results will be presented via different analyses, in which we will compare the original aircraft and mission with the alternative missions. This will allow checking the CO2 reduction and the structural changes in order to integrate the systems and the interfaces needed for the new configuration. The final calculations will give the final volume for the tank, the fuel cells and the batteries. Different tables will show the weight reduction as well as the reduction of the emissions with the different materials incorporated. Finally, we will state the problems that have come along with this process and the conclusions that will guide to the next steps.

Acknowledgement: The research presented in this paper has also been performed within the framework of the HERFUSE project (Hybrid-Electric Regional FUSelage & Empennages), which has received funding from the European Union Clean Aviation Programme under Grant Agreement No. 101140567. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation. Neither the European Union nor the granting authority can be held responsible for them.

Innovative Floor Structure Concepts and Enabling Technologies for the Integration of Hybrid-Electric Regional Aircraft

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1. Introduction / Objectives

The Clean Aviation SRIA drives the integration of disruptive technologies such as Hybrid-Electric propulsion and liquid hydrogen systems to achieve up to 50% emissions reduction for regional aircraft, significantly impacting configuration and structural design.
Montana Aerospace, through its subsidiary ASCO, is an experienced supplier of fuselage floor grid structures—including cross beams and seat tracks—manufactured from aluminium and titanium extrusions for legacy platforms such as the A320 and A350. Building on this expertise, ASCO contributes to the HERFUSE project by developing an innovative floor structure adapted to these new architectures.
A key requirement is the integration of hydrogen systems within the fuselage while achieving an overall 8% weight reduction at fuselage and empennage level. This study focuses on the central and rear floor sections, addressing increased volume, weight, and load complexity to enable efficient integration and optimized structural performance.

2. Methodology

The primary driver for the floor design is the achievement of a minimum 8% weight reduction, required to meaningfully contribute to the overall structural weight targets.. This objective must be met while accommodating additional functional requirements, notably the integration of battery systems alongside the conventional passenger load.
The incorporation of battery packs and fuel cells significantly alters the fuselage architecture, resulting in a a non-circular/flattened lower section. This non-circular geometry introduces additional structural challenges, particularly in terms of load distribution and structural efficiency.
The study is structured in several key steps. The first phase focuses on identifying the main design drivers, including crashworthiness requirements, the impact of battery attachment on the floor structure, internal pressure loads, and external fuselage loading conditions. Finite element models are developed to estimate internal loads and stress distributions, providing the basis for subsequent design stages.
An appropriate material selection review has been performed in collaboration with UAC, part of Montana Aerospace, to identify the best compromise between mechanical performance and weight.
In a second phase, innovative structural concepts are analyzed and benchmarked to enhance structural efficiency and improve the buy-to-fly ratio, including the use of advanced high stiffness-to-weight materials, the replacement of conventional I-shaped crossbeams with closed-section extrusions, the application of structural bonding as an alternative to mechanical fastening, and the evaluation of friction stir welding for extruded components.
The final phase focuses on design optimization, incorporating the outcomes of the preceding trade-off studies. Weight reduction is pursued through detailed finite element analyses combined with automated optimization loops, ensuring efficient iteration. Each structural component is assessed with the objective of minimizing weight while maintaining compliance with all performance and certification requirements.

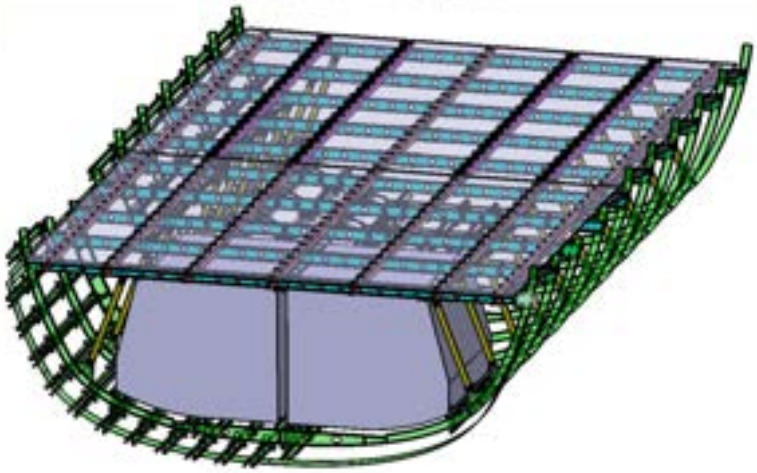


Figure 1. *Floor Structure overview with battery integration (HERFUSE Section 13)*

3. Results / Conclusions

To support the target of a 50% reduction in emissions through technological advancements, the floor structure of the new regional aircraft studied within the HERFUSE project under Clean Aviation must achieve an 8% weight reduction while accommodating the additional loads associated with battery integration.
This paper presents some conclusions about benchmarking activities focused on structural improvements The outcomes of the final sizing process, together with the associated structural performance results, are also discussed.
In addition, a set of key recommendations and identified challenges is provided, highlighting critical enablers as well as remaining hurdles for the successful implementation of the proposed design concepts.

Acknowledgement: This research was funded by Hybrid-Electric Regional Fuselage & Empennages (HERFUSE). This project has received funding from the Clean Aviation Joint Undertaking under the European Union's Horizon Europe research and innovation program under grant agreement No. 101140567

Optimization of a Horizontal Tail Plane under Longitudinal Stability Constraints

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1. Introduction / Objectives

This paper extends the state-of-the art gradient-based multidisciplinary optimization (MDO) methodology to the optimization of horizontal-tail-planes (HTPs), demonstrated for the DLR-F25 industry-representative short-to-medium range research aircraft . These developments aim towards the broader goal of integrating high-fidelity analysis and optimization into aircraft conceptual design. Replacing empirical and low-fidelity conceptual design methods like tail volume estimations with higher-fidelity methods increases general performance of designs and provides more detailed knowledge about the design in early design stages. A modular multidisciplinary optimization process based on high-fidelity methods is implemented to optimize tail configuration for aerodynamic performance under longitudinal static stability

margin constraints. These constraints assure that the functionality of the tail is not compromised by the performance optimization. The activity is part of a longer-term objective to incrementally extend the high-fidelity CFD/CSM-based MDO capabilities existing at DLR with an increasing number of flight physics-constraints based on highly accurate analyses.

2. Methodology

The optimization shown in the paper aims to optimize in this case the fuel burn of the aircraft at a level cruise-flight condition, while satisfying a prescribed static margin (K_m). The optimization problem is formulated as:

$$\begin{aligned} \underset{\boldsymbol{x}}{minimize} \quad & m_{fuel}(\boldsymbol{x}) \\ subject\ to \quad & C_L(\boldsymbol{x}) = C_{L,target}\,, \\ & C_{m_y}(\boldsymbol{x}) = 0\,, \\ & K_m(\boldsymbol{x}) = K_{m,target} \end{aligned}$$

DLR's CFD-solver TAU is used for high-fidelity-based aerodynamic performance prediction using trimming with the angle of attack and HTP to maintain constant lift and pitching moment equilibrium.
The static margin of the aircraft is computed using central finite-differences with respect to the angle of attack. Sensitivities of the design variables are computed using the adjoint method to cover large design spaces efficiently and corrected for the trim condition . The aerodynamic performance analysis, geometry updates, and sensitivity computation of rigid or flexible aircraft is orchestrated by DLR's multidisciplinary analysis kernel FSDLRControl. FSDLRControl's modular design defines the process and interdisciplinary couplings using the FlowSimulator framework independently of the specific disciplinary solver methods, thus allowing to exchange methods like the CFD-/CSM-solvers or the geometry parameterization. Apart from a differentiated structural mechanics solver, Airbus' structural optimization process Lagrange also provides the active-set capability-featuring NLPQL optimizer . Different static margin constraints are applied to demonstrate the capability of the overall method to influence and enforce the static margin of the aircraft.

3. Results / Conclusions

The paper discusses the methodology chosen for introducing longitudinal stability constraints into the MDO and outlines all process ingredients. It further discusses the obstacles and problems faced during the undertaking to shape the process. The results of a step size study aiming to obtain an appropriate step size for the central finite differencing of the static margin are presented. Sensitivities of the performance parameters and the static margin constraint are compared against finite differences for validation.
Optimization results demonstrate the process' ability to enforce different prescribed static margin values. The optimized designs are compared with results from a tail volume analysis on the same aircraft configuration and with results from an unconstrained optimization.

Acknowledgement: The research presented in this paper is performed within the framework of the HERFUSE project, which has received funding from the European Union Clean Aviation Program under Grant Agreement No. 101140567. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation.

Topology optimization of aircraft fuselage frame

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1. Introduction

Topology optimization is a computational design method used to determine the most efficient material distribution within a defined design space, subject to loads, boundary conditions, and performance constraints. For an aircraft part, this approach supports minimize structural weight while maintaining required stiffness, strength, and other parameters. By iteratively removing non-essential material, topology optimization reveals innovative load paths and highly efficient geometries that are difficult to achieve with traditional design methods. This is particularly important in aerospace applications, where reducing mass leads to improved fuel efficiency and lower emissions. The optimized fuselage frame must also satisfy manufacturing, fatigue, and certification constraints. As a result, topology optimization is often combined with advanced materials and new manufacturing techniques to realize complex, lightweight, and high-performance structural components. This paper will present outcomes of study made to prepare final design of metallic panel frame, that will be tested in frame of the HERFUSE project.

2. Methodology

The topology optimization of a fuselage frame begins with defining the design domain, which represents the allowable geometric space for the frame within the fuselage section. Non-design regions, such as attachment points, cut-outs, and interfaces with skin panels or stringers, are preserved. Material properties, in presented case, aluminum alloys are assigned. Next, load cases and boundary conditions are established based on realistic operating scenarios, including cabin pressurization, bending loads, shear forces, and local stress concentrations from attachments. Multiple load cases are often combined using weighted factors to reflect critical flight conditions and in this point it will be described in case of frame loads.

The optimization problem is then formulated, most commonly using the density-based SIMP (Solid Isotropic Material with Penalization) method. The objective function typically aims to minimize structural compliance (maximize stiffness) or mass while satisfying constraints such as stress limits, displacement bounds, and buckling resistance. A prescribed volume fraction ensures significant weight reduction. Setup of analysis is crucial to obtain good results what will be the part of description in final document.

The design domain is discretized using finite element analysis (FEA), and the material distribution is iteratively updated. Penalization schemes are applied to drive the solution toward discrete solid–void configurations. Filtering techniques are used to control numerical instabilities such as checkerboarding and mesh dependency.

Once convergence is achieved, the resulting topology is interpreted and refined into a manufacturable geometry. This step involves smoothing irregular features, incorporating minimum thickness constraints, and ensuring compatibility with manufacturing methods such as machining in case of proposed frame design.
Finally, the optimized design undergoes validation and verification through detailed FEA, fatigue assessment, and certification checks. Iterative refinement may be required to balance performance, manufacturability, and regulatory compliance, what also will be highlighted in final paper.
Final paper will focus of practical approach to Topology Optimization with detailed description of above mentioned steps, summarized on fig.1, using as an example fuselage frame from test panel, that will be validated by several load cases during final test campaign of the HERFUSE project.

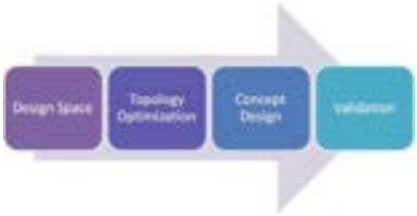


Figure 1. *Topology optimization steps .*

3. Results and conclusions

The outcome of the analysis will be presented in the final document, including a comprehensive description of the methodology and the influence of the previously described steps. The final results, as shown in Figure 2, serve as an example that will be used for a detailed assessment of the topology optimization applied to the frame of a metallic panel. This structure will be tested during the final stage of the HERFUSE project, and the obtained results will support the final investigation as well as the FEM verification of the proposed solutions.
The design of the frame, along with the corresponding results and conclusions, is strongly dependent on the requirements of the test stand and the execution procedure of the tests. These aspects will also be addressed in the final discussion, where advantages and limitations will be clearly outlined to demonstrate the progression from initial assumptions to the final optimized solution.



Figure 2. *Frame of test panel before and after optimization.*

Manufacturing Strategy for an Integrated Composite Fuselage Lateral Panel with one-shot Liquid Resin Infusion

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1. Introduction / Objectives

The transition toward hybrid-electric aviation requires lightweight and sustainable structural solutions capable of reducing both aircraft weight and manufacturing environmental impact. In this context, the HERFUSE project investigates novel manufacturing technologies for integrated composite fuselage structures with enhanced structural efficiency and improved production automation.

This work focuses on the development of a Liquid Resin Infusion (LRI) process for the manufacturing of a fuselage lateral panel using dry fibre preforms. The proposed approach aims to integrate stiffening elements, such as stringers and frames, directly into the skin during a single-shot manufacturing process, avoiding conventional joining operations and reducing the number of manufacturing steps. Compared with state-of-the-art prepreg/autoclave technologies, the use of dry reinforcements enables easier material handling, facilitates automation strategies for preforming and lay-up, and eliminates refrigerated storage and repeated autoclave consolidation cycles.

The objective of this work is to define, validate, and scale an infusion strategy for highly integrated fuselage structures while assessing the manufacturing challenges associated with large and geometrically complex components.

2. Methodology

The development methodology was based on a progressive validation approach combining experimental trials and numerical simulations. First, a scaled demonstrator representative of the fuselage lateral panel architecture was designed and manufactured to define the infusion strategy and evaluate the manufacturability of integrated stiffened structures.

The scaled demonstrator consisted of a 500 × 500 mm flat composite panel integrating one stringer and one frame co-infused in a single process step. Dry fibre reinforcements were laminated and formed in a membrane press prior to resin infusion. Different infusion configurations were evaluated to analyse resin flow behaviour, permeability effects, filling homogeneity, and potential defect generation areas such as dry spots or resin accumulation zones.

Finite Element Method (FEM)-based simulations were used to support the process definition and optimize the infusion strategy. The simulations provided guidance regarding resin flow progression, inlet and outlet positioning, filling times, and potential risk areas associated with the integrated geometry. Numerical results were correlated with the experimental trials to improve process robustness and support scaling activities.

Based on the knowledge acquired during the subcomponent validation phase, the process was transferred to the manufacturing of a full-scale fuselage lateral panel of the final HERFUSE architecture. The demonstrator integrates five stringers and three frames over a curved skin geometry and is intended to be manufactured through a single-shot infusion process. The scale-up activity includes the adaptation of tooling concepts, vacuum strategies, resin distribution systems, and preform stabilization methods required for large integrated aerostructures.

The work also evaluates the manufacturing advantages associated with dry fibre technologies, including improved material handling, reduced process complexity, and

increased opportunities for automation compared with conventional prepreg-based manufacturing routes.

3. Results / Conclusions

The conducted work demonstrates the feasibility of manufacturing integrated fuselage structures using a single-shot LRI approach. The scaled demonstrator trials enabled the definition and validation of suitable infusion strategies for highly integrated composite architectures while identifying key process parameters and manufacturing challenges associated with resin distribution and geometry complexity.

The combination of experimental activities and FEM-supported simulations proved effective for process optimization and risk mitigation during technology scale-up. Preliminary developments indicate that the proposed manufacturing route can significantly reduce assembly operations and improve structural integration compared with conventional prepreg/autoclave processes.

Current activities are focused on transferring the validated methodology to a full-scale curved fuselage lateral panel integrating multiple stringers and frames. The expected outcomes of this work include weight reduction, manufacturing simplification, lower energy consumption, and enhanced automation potential, contributing to more sustainable and cost-efficient production solutions for future hybrid-electric aircraft structures.

Conceptual Design of an Integrated Monoblock Composite HTP for Next-Generation Regional Aircraft

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[2] Leonardo, Italy

1. Introduction / Objectives

Sustainable regional aviation is driving the development of lighter and more efficient aircraft structures, capable of reducing fuel consumption and emissions, In this context, the present study investigates an integrated composite monoblock architecture for the Horizontal Tail Plane (HTP) of next-generation regional aircraft, focusing on structural weight reduction, assembly simplification, and improved load transfer efficiency within the empennage structure.

The main objective of the work is to improve structural efficiency while simplifying assembly operations through the reduction of mechanical joints, fasteners, and subcomponents present in the baseline HTP configuration of the ATR72-600 reference platform. The proposed concept introduces a co-cured multi-spar composite structure integrating the lower skin and primary load-carrying members into a single structural assembly.

Compared to the current state of the art, typically based on segmented composite subassemblies connected through central boxes and extensive fastening systems, the proposed configuration aims to enhance load transfer continuity, reduce structural mass, and improve manufacturing integration, while maintaining the stiffness and strength requirements necessary for aeroelastic stability and flight safety.

2. Methodology

The development of the horizontal tailplane (HTP) concept focused on achieving an optimal balance between structural efficiency, manufacturability, and aircraft integration. The study began with the definition of the main aerodynamic and geometric constraints derived from the reference configuration of the regional aircraft and the Top-Level Aircraft Requirements (TLARs) defined and published within the HERA project framework.

The structural architecture was developed using a multi-spar configuration and integrated with the lower skin via a co-polymerization process. Particular attention was paid to the redesign of the tailplane center section, identified as the most critical area between the horizontal tailplane (HTP) and the vertical tailplane (VTP). The conventional center box configuration was progressively replaced by an integrated monoblock configuration, aimed at minimizing structural discontinuities and reducing the number of mechanical fasteners and assembly interfaces.

Particular attention was paid to the alignment between the structural elements of the HTP and VTP to improve load transfer continuity and reduce local stress concentrations at the fastening interfaces. Reinforcing ribs and dedicated metal fittings were introduced in the central region to ensure adequate stiffness and structural integrity in the connection area.

A CAD model of the HTP structural box was developed to evaluate geometric integration, assembly feasibility, and manufacturability constraints associated with the new technologies and the new configuration. The entire HTP was optimized, considering both structural performance and assembly accessibility.

Finite element modeling (FEM) activities were performed to evaluate the most critical regions subjected to combined bending and torsional loads.

A comparative evaluation with the ATR 72-600 was conducted to estimate the potential structural weight reduction achievable with the proposed concept.



Figure 1. Assembling scheme of the upper panel.

3. Results / Conclusions

The proposed integrated monoblock composite HTP configuration demonstrated significant potential in terms of structural efficiency, weight reduction, and assembly simplification for next-generation regional aircraft applications. Preliminary assessments showed that the elimination of the conventional central box, overlap joints, and numerous mechanical fasteners enables a total estimated structural weight reduction of approximately 10.3 kg, corresponding to about 12.3% of the reference HTP box mass.

The integrated co-cured architecture also improves structural continuity and load transfer between HTP and VTP, supporting a more uniform stress distribution within the central attachment region. In addition to mass reduction, the proposed configuration reduces the number of structural components and assembly interfaces, potentially improving manufacturing efficiency and reducing production complexity.

The preliminary assessment highlights the potential benefits of integrated monoblock composite HTP architectures in reducing structural mass and assembly complexity while improving structural load transfer efficiency.

Data-Driven Models for Aeronautical Design and Optimization

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1. Introduction / Objectives

The growing complexity of aeronautical design requires fast, reliable, and physically consistent predictive tools to complement high-fidelity simulations. While CFD and FEM provide accuracy, their computational cost limits large-scale studies. Data-driven methods offer efficient alternatives across multiple domains. This work reviews machine learning advances for aerodynamic prediction, fatigue estimation, and flow-field generation, highlighting techniques such as clustering-enhanced regression, physics-consistent surrogates , and diffusion-based models , which improve accuracy while reducing cost and accelerating industrial design workflows.

2. Methodology

A first contribution addresses fatigue life prediction through supervised learning models trained on operational flight parameters, replacing traditional workflows involving FEM simulations, load spectrum derivation, and cycle counting. The resulting pipeline delivers fast and accurate estimates, supported by statistical validation and uncertainty quantification for robustness and certification readiness . A second approach introduces physics-consistent surrogate models to predict aerodynamic pressure fields across multiple meshes and flow conditions. It combines interpolation across operating conditions with geometry-based mappings, while a constrained optimization step ensures conservation of integral quantities for physically consistent results. To better capture nonlinear aerodynamic effects, alternative modelling strategies are explored,

improving the representation of localized phenomena such as transonic discontinuities and enhancing predictive accuracy. Finally, generative models based on diffusion and flow matching are applied to CFD data, enabling controlled generation of pressure fields conditioned on physical parameters, with improved scalability and accuracy over conventional methods . The methodologies presented here are available in the open source code PyLOM .

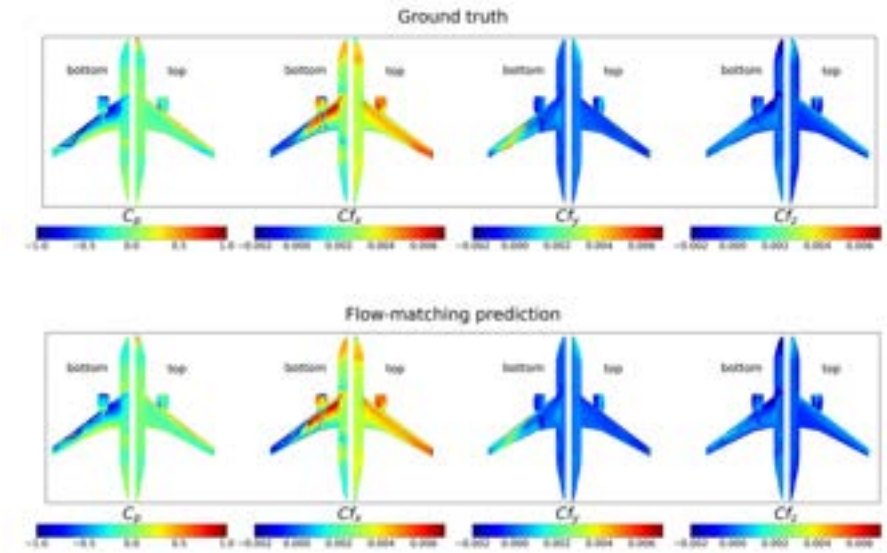


Figure 20. Comparison between (ground truth) CFD pressure/friction coefficient fields (top panels) and the prediction generated by the DiT flow-matching model (bottom panels). Figure extracted from [2]

3. Results / Conclusions

Data-driven models significantly enhance aeronautical design by reducing computational cost while maintaining high accuracy. Fatigue prediction, physics-consistent surrogates, clustering-based regression, and generative models improve reliability, capture complex nonlinear effects, and enable realistic flow synthesis. Together, these approaches form a scalable framework that complements traditional simulations, supporting faster design iterations and advancing data-driven aerospace engineering.

Acknowledgement: This project has received funding from the Project TIFON (No. PLEC2023-010251) funded by MCIN/AEI/10.13039/501100011033, Spain. This project has received funding from the Clean Aviation Joint Undertaking under the European Union's Horizon Europe research and innovation programme under Grant Agreement HERFUSE No. 101140567 and HERA No. 101102007. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or CAJU. Neither the European Union nor the granting authority can be held responsible for them.

Morphing Elevator Aero Design Applying Evolutionary Algorithm-Based Optimization and Radial Basis Functions

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1. Introduction / Objectives

Aviation industry is experiencing profound transformations, largely driven by the imperative to minimize its environmental impact. In particular, the Advisory Council for Aviation Research and Innovation in Europe (ACARE), through its Flightpath 2050 initiative, together with the European Union's (EU) climate strategies, has established ambitious goals, including a 75% reduction in CO_2 emissions per passenger-kilometer, a 90% decrease in NO_x emissions, and a 65% reduction in perceived noise levels by 2050.
To meet these targets, innovative technologies, e.g. morphing technology, which has been studied over the last years, but mainly for wing surface, are needed.
This study is about the two-dimensional (2D) aerodynamic design of a morphing elevator for the horizontal tailplane (HTP) of a green regional aircraft, developed through numerical optimization techniques. The goal is to improve aircraft performance under realistic flight regimes by means of a morphing trailing edge capable of modifying its camber distribution.

2. Methodology

Studies have been carried out using a CIRA in-house optimization tool developed over years, which can manage different optimization algorithms. The one used for the current application is the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) **Error! Reference source not found.** evolutionary algorithm, which drives the airfoil geometry update with imposed constraints and objective functions.
The update of the geometry is obtained by means of another CIRA in-house routine performing Radial Basis Function (RBFs) interpolation on the assigned geometry, in accordance with the optimization input. Four design variables have been considered to drive geometry updates: the location of elevator hinge, the rotation corresponding to this point, a second point along the elevator hinge around which a second rotation of the elevator is imposed.
The aerodynamic evaluation has been performed using a 2D viscous–inviscid interaction approach, which combines a Euler solver for the external inviscid flow with a boundary-layer solver that accounts for laminar, transitional, and turbulent flow regions. A strong coupling strategy ensures accurate interaction between viscous and inviscid effects**Error! Reference source not found.**.
The activities described in this paper have been carried out within HERFUSE (Hybrid-Electric Regional FUSelage & Empennages) project; which has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101140567.
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or of the granting authority. Neither the European Union nor the granting authority can be held responsible for them.

3. Results / Conclusions

The findings suggest that the integration of morphing technologies into tailplane design represents a promising approach for the development of next-generation aircraft with

improved aerodynamic performance (see Figure 1). The optimized geometries derived in this work have been used as reference shapes for subsequent structural analyses and for the design of the actuation mechanisms driving the morphing elevator.

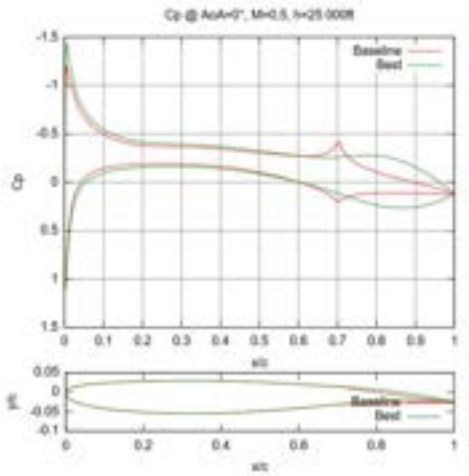


Figure 1. *Example of pressure coefficient distribution and airfoil geometry modification: baseline (red) vs optimized (green).*

Investigation of novel energy systems structural integrators in regional aircraft

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1. Introduction / Objectives

Achieving the goals set by the Clean Aviation Joint Undertaking to meet the net zero emissions requirements until the year 2050 requires radical redesign of aircraft and the inclusion of novel and disruptive technologies. Liquid hydrogen (LH_2) as an energy source is viewed as a potential path to achieve carbon neutral commercial aviation, albeit accompanied by a plethora of structural, thermal and safety challenges that still need to be resolved. In the framework of Hybrid Electric Regional Fuselage & Empennages' Clean Aviation project HERFUSE, the structural integration of Hybrid Electric energy systems utilizing LH_2 in regional commuter aircraft is investigated. Implementation of these systems necessitates the development of innovative structural interfaces between the systems and the fuselage. Focusing on operational and crashworthiness requirements, a structural integration solution optimizing the load paths and incorporating impact energy absorbing elements is being developed to meet the safety and damage tolerance requirements as well as enabling quick tank extraction from the fuselage for refueling.

2. Methodology

Investigation of the structure's response via Finite Element (FE) modelling under static inertial load cases and certification specifications as well as dynamic impact analysis is required. Initially, identification of the spatial requirements as well as critical load paths, considering the surrounding structure in combination with operability requirements is performed. The tank is

located within the fuselage aft of the pressurized cabin's bulkhead and, therefore, adequate restraint is required to ensure the safety of the cabin. ANSYS Workbench 2025R1 with its integrated Computer Aided Design software SpaceClaim is used to develop and optimize a structural integration concept of a LH_2 tank into the aircraft fuselage. The appropriate locations of the tank attachment points are selected, followed by structural analysis under longitudinal, vertical and lateral inertial loads to assess deformation and stress levels. Utilizing the FE software capabilities, the 3D CAD model was converted into a FE model, shown in **Error! Reference source not found.**, which was used to calculate the fuselage and tank structures displacements, stresses and strains. Based on these results, modifications to the concept were performed to derive an optimized solution. The investigation will be accompanied by virtual drop tests in LS-DYNA to assess the response of the structure under dynamic impact loads.

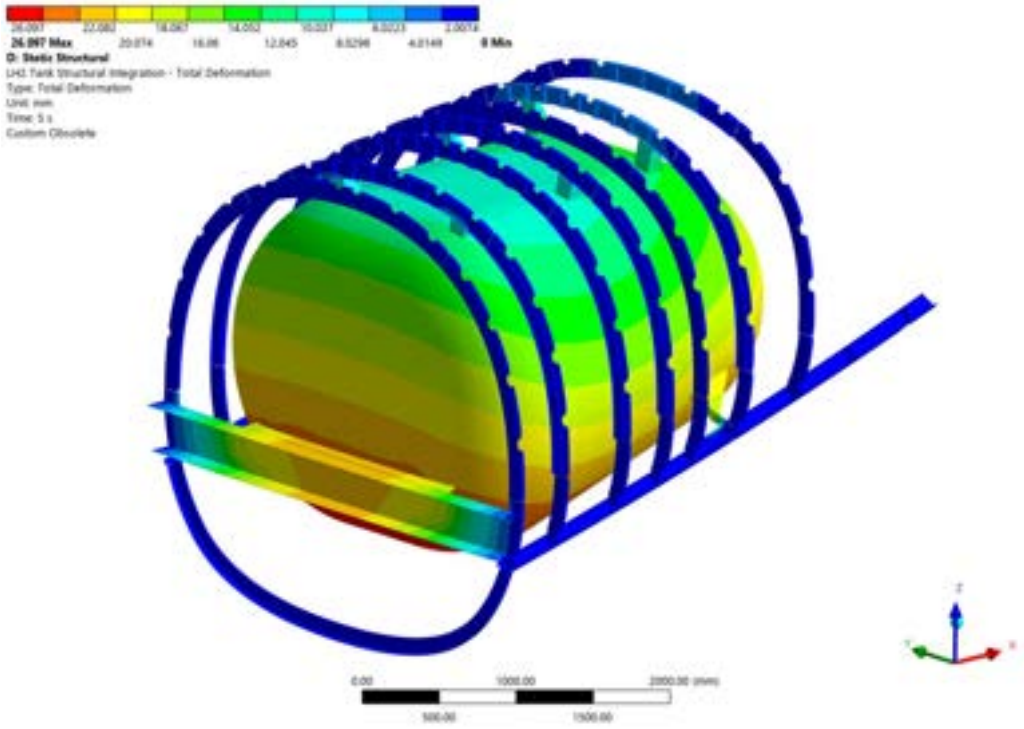


Figure 1: *HER aircraft aft fuselage section with the LH2 tank integrated – Deformation contour plot*

3. Results / Conclusions

The results of the analysis indicate that the proposed integration solution is applicable, as well as an optimized solution can be derived. The conclusions drawn from the static inertial load case indicate that the forward longitudinal load case requires significant optimization to effectively transfer the loads from the tank to the fuselage. Dynamic impact analysis highlights the importance of the energy absorbing capacity of the proposed concept.

Acknowledgement: This research was funded by Hybrid Electric Regional Fuselage & Empennages (HERFUSE). This project has received funding from the Clean Aviation Joint

Undertaking under the European Union's Horizon Europe research and innovation program under grant agreement ID 101140567.

Structural Assessment and Pressurization Challenges of Unconventional Non-Circular Fuselage Sections for Hybrid-Electric Regional Aircraft: A HERFUSE Project Case Study

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1. Introduction / Objectives

The integration of hybrid-electric propulsion systems in regional aviation necessitates radical departures from conventional airframe architectures. Within the HERFUSE project, novel fuselage configurations are being investigated to accommodate bulky components such as battery packs, power electronics, and thermal management systems, leading to unconventional, non-circular cross-sections. Unlike standard cylindrical fuselages, where internal pressure is efficiently carried by membrane hoop tension, non-circular geometries induce significant bending stresses that compromise structural weight efficiency and CS-25 certification compliance.
The primary objective of this work is to provide a comprehensive structural assessment of the forward fuselage section for a CS-25 hybrid-electric regional aircraft, focusing on the stress and displacement distribution induced by cabin pressurization in non-standard shapes. The technological innovation lies in the parametric modeling approach and high-fidelity Finite Element Analysis (FEA) applied to disruptive fuselage configurations, establishing a robust framework for the structural evaluation and future optimization of next-generation sustainable airframes.

2. Methodology

The analysis is conducted on a representative forward fuselage section of a CS-25 hybrid-electric regional aircraft developed within the HERFUSE project. Starting from a master surface with a non-circular cross-section, a CAD model of Fuselage Section 13 was developed to provide a starting point for the subsequent Finite Element Model used in the stress analysis. This CAD model serves as the foundation for mesh generation and boundary condition definition in the FEA workflow.
High-fidelity FEA investigation is dedicated to mapping the critical structural challenges inherent to non-circular fuselage sections. Unlike conventional cylindrical fuselages where internal pressure is carried primarily through membrane hoop tension, the non-circular geometry introduces significant bending stresses that concentrate in specific regions, particularly at transitions between flat and curved wall segments. These stress concentrations compromise structural efficiency and raise concerns regarding CS-25 certification compliance.

To address these criticalities, a methodological stress report workflow is proposed to set up a future iterative optimization process. Individual stress and strain problematic areas are systematically identified to evaluate potential localized design modifications. The underlying investigation strategy explores two primary approaches: thickness variations in critical regions and localized design corrections targeting specific stress concentration zones. Furthermore, innovative connection structures between structural elements are investigated, specifically at the interfaces between frames and skin panels, to evaluate load transfer efficiency and mitigate bending moments at critical junctions. The analytical procedure allows for localized trade-off evaluations rather than global overdesign, aiming to maintain overall structural mass within acceptable limits while assessing target stress levels.

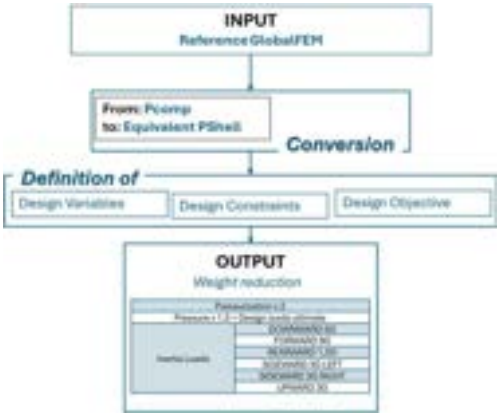


Figure 1. *Iterative-Optimization Process.*

3. Results / Conclusions

Preliminary structural assessments show that non-circular fuselage sections generate severe bending stresses and large deformations under cabin pressurization, unlike the mainly membrane-driven response of conventional cylindrical fuselages. Stress concentrations are primarily located near high-curvature regions and geometric discontinuities, leading to increased structural inefficiency that represents the main challenge for this architecture.
The study demonstrates a clear trade-off between internal volume optimization and structural mass penalties. Configurations with improved volumetric efficiency exhibit higher peak stresses and increased deformation levels, indicating a demanding path for structural performance compliance under pressurization loads.
Overall, the proposed framework provides a consistent, high-fidelity stress report methodology for evaluating unconventional fuselage designs and supports early-stage decision-making in the structural design of hybrid-electric regional aircraft. The findings directly contribute to the ongoing feasibility and structural viability assessment of non-cylindrical fuselage architectures for future low-emission aviation concepts, establishing the baseline for upcoming numerical optimization phases.

FACELIFT project: innovative fluidic actuators to improve stealth and maneuverability of military aircraft

Chaired by:
Mr. Jernej Drofelnik (Pipistrel Aircraft, Slovenia) & Mr. David Ferris (Cedrat Technologies, France)

Switching Jet Actuators for Separation Control on Lifting Surfaces

Julien Weiss[1], Stephan Löffler[2], Thomas Grund[1], Jérôme Delva[3], Luka Porenta[4], Jernej Drofelnik[4]
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[2] Autodesk GmbH, Germany
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1. Introduction / Objectives

The objective of separation control is to enhance the effectiveness and efficiency of aerodynamic systems that are naturally limited by boundary-layer separation. Separation control may be used on stealth aircraft, where requirements to minimize radar cross section usually result in aircraft control surfaces designed with a smaller scale than would be selected if aerodynamic requirements were prevalent. The small scale of these control surfaces implies their usage at large deflection angles, which leads to design points relatively close to their maximum force coefficient, where flow separation naturally occurs. This, in turn, limits vehicle maneuverability in off-design conditions. To circumvent this limitation, the FACELIFT project aims at using separation control to influence the airflow on lifting surfaces and thereby enhance their aerodynamic performance.
Within FACELIFT, two actuator types are being evaluated for separation control on the lifting surfaces of stealth aircraft: Synthetic Jet Actuators (SJA) and Switching Jet Actuators (SWJ). The objective of the present contribution is to describe the latter type of actuators.

2. Methodology

The basic idea of separation control with SWJ is to inject high momentum fluid into a separating boundary layer where the momentum is low. This energizes the low-speed region and thereby maintains the boundary layer attached to the surface . The mass injection is done in an unsteady way by using a fluidic oscillator that switches the momentum of a steady stream of air between pairs of thin slots opened in the surface of interest. Compared to classical steady blowing, this has been shown to increase efficiency by limiting the injected mass flow required to control separation.
The function principle of the SWJ is shown in figure 1a: a steady stream of air is injected into a plenum with sufficient pressure to ensure a prescribed mass flow rate. Upon passing through a nozzle, the air stream is directed to either one of two distribution channels (highlighted in blue or red) separated by a splitter. When the air flows through the blue channel, it can reach three outlets, also shown in blue. On the other hand, when the air flows through the red channel, it can only reach the three red outlets. The amount of time that the flow spends in the blue or

red distribution channel depends on the length and diameter of the feedback loop that connects each channel back to the nozzle. The combination of actuator geometry and overall mass flow supply defines the switching frequency of the air through the nozzles, as demonstrated in.
In practice, the length requirement of the different channels often conflicts with the limited size of the aerodynamic surface in which the actuator is to be installed. To solve this issue, both the main distribution channels and the feedback loops may be folded into a three-dimensional actuator volume, as shown in figure 1b and discussed in .

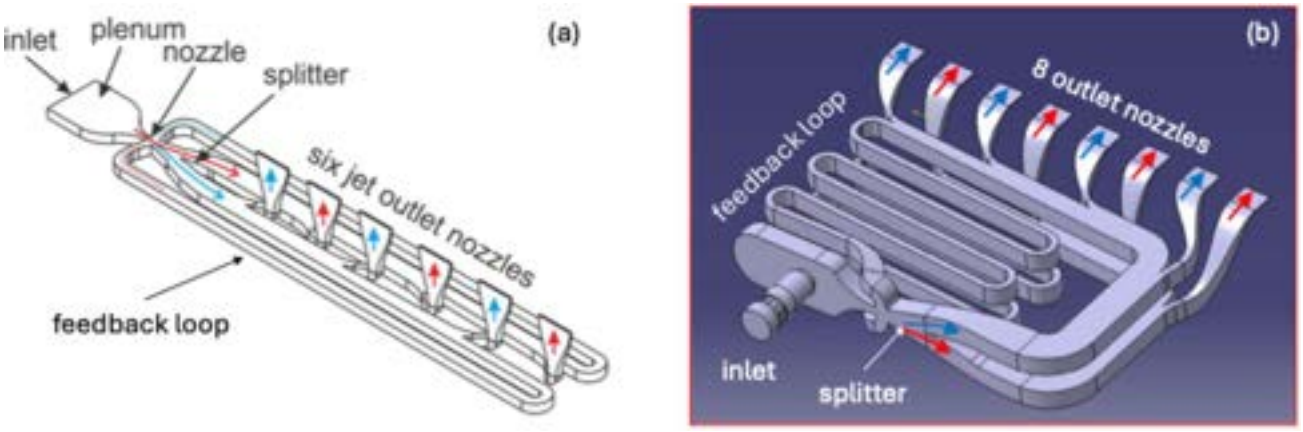


***Figure 1**: Illustration of SWJ operating principle: unfolded 6-nozzles actuator (a) and folded 8-nozzles actuator used within FACELIFT*

3. Results / Conclusions

In addition to their function principle summarized herein, the manufacturing, installation, and testing of the FACELIFT SWJs will be discussed in the conference presentation.

Piezoelectric Synthetic Jet Actuator embedded in aircraft wingtip for stealth application

A. Barnique[1], G. Aigouy[1], E. Eglinger[2], J. Delva[2], F. Ternoy[2], J. Roháč[3], D. Ferris[1], G. Mansuy[1]
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[2] ONERA, France
[3] ESC Defence, Czech Republic

1. Introduction / Objectives

In the frame of the European Defence Fund, project FACELIFT (funded through grant agreement No. 101102557) has the main objective of improving the stealthiness and maneuverability of military capabilities such as the European MALE-RPAS Eurodrone. CEDRAT TECHNOLOGIES is involved in this project to design and manufacture Synthetic Jet Actuators (SJA). SJA are pistons producing vortical structures that reattach separated flow or modify boundary layer behavior to reattach the flow with a higher angle of aileron deflection. The targeted jet velocity is the speed of sound to maximize the desired effect on the aircraft. The actuator used in the SJA is an Amplified Piezo Actuator, a patented design that combines

high dynamic and amplified motion. From the previous project called SYNJET3C where the design wasn't reliable enough, we added the following improvements: 2 APA in series with additional amplification, all in parallel twice to increase robustness. For the first time, this technology will be tested in flight.

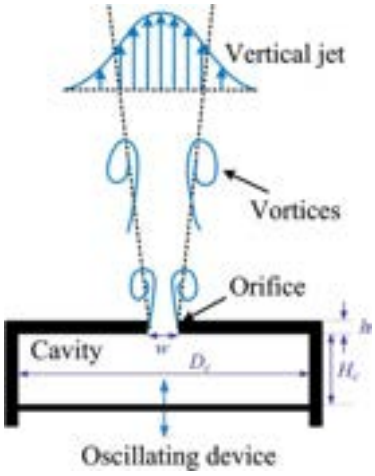


Figure 1. *SJA working principle.*

2. Methodology

Piezoelectric SJA is not a new technology, and previous projects gave a good starting point but also technical challenges to resolve. For example, the APA changed from previous projects to improve its robustness.

ONERA team used this APA to design and build a rotative concept SJA choosing force over displacement. Cedrat Technologies team proposed a linear concept with a 2nd amplification system to reach higher displacement and speed.

To optimize the performances with a large number of parameters, the linear prototype had a lot of adjustable dimensions (chamber length, size of the slit, stiffness and moving mass, …).

Both concepts were assessed in laboratory conditions, and all parameters of interest were measured: air pressure inside the chamber, jet velocity, current, voltage and temperature.

Then a comparison was made based on robustness, actuation frequency, jet velocity and current needs. The linear concept was chosen.

The next phase was the redesign to make the integration in the aircraft wingtip possible: Weight optimization, compactness, safe wire routing, design of the health monitoring sensors and conditioners.

The manufacturing and test of the first 7 SJA has been done at Cedrat Technologies. Then it was integrated into the wingtip in collaboration with the aircraft manufacturer before going to the wind tunnel test.

Once the results are confirmed, the 7 SJA of the other wingtip were designed, manufactured and tested as well.

3. Results / Conclusions

During wind tunnel laboratory tests, the Synthetic Jet Actuator reached a piston stroke of

2mm at 235Hz, creating a jet speed over 200m/s. The health monitoring sensor designed is a Eddy Current Sensor with capability of measuring this high stroke.
The compactness and the weight targets were achieved to allow integration in the aircraft. After integration in the wingtip, the wind tunnel assessment demonstrated that for a flow velocity of 30 m/s and aileron angle of 20°, the SJA can fully reattach the flow on the aileron. At the end of the project (July 2026) this SJA system is tested in an aircraft in flight conditions.

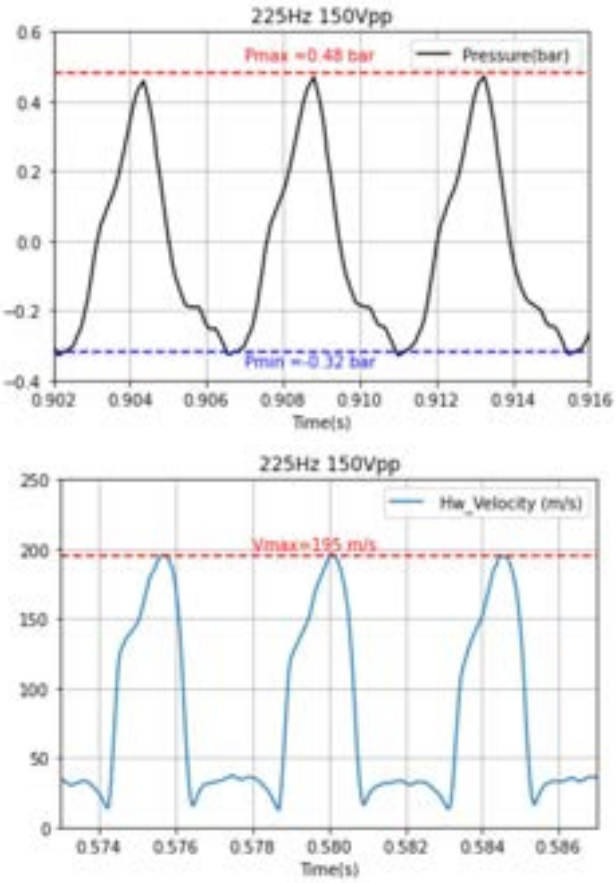


Figure 2. *Laboratory assessment results.*

High power electronics for synthetic jet actuators

Jan Rohac, Vitalij Velicko, Ales Honomichl
esc Defence s.r.o., Czechia

1. Introduction / Objectives

In the frame of the European Defence Fund, project FACELIFT (funded through grant agreement No. 101102557) has the main objective of improving the stealthiness and maneuverability of military capabilities such as the European MALE-RPAS Eurodrone. esc Defence s.r.o. (ESC) has been responsible within the project for the design and development of the electronics for the actuators' control as well as for actuators' and aircraft performance monitoring. Even though the paper deals with the high-power electronics, it also provides the overall system architecture for clear understanding of aspects

considered thought the entire development cycle. The FACELIFT project was focused on two technologies of the flow control actuators, i.e. synthetic jet and switching jet actuators (SJAs/SWJs). For both assemblies the electronics installation suffers from a high level of commonalities, except for the part related to the high-power electronics which is dedicated rather to the SJA assembly.

2. Methodology

The whole electrical scheme of the SJA assembly is depicted in Figure 1. The scheme can be split into two parts, i.e. the part incorporated in the wingtips (green background area) used at both sides of the aircraft (A/C) and the part incorporated into the central A/C part. Blue background area is used to indicate a principle part of the power distribution unit which provides the power adaptation and its protection within the power source side and electrical components of the SJA assembly. Data acquisition units (DAQs) provide the data handling at the side of a wingtip and establish the communication with other signal/data conditioners (CONs) and SJAs' position sensing units, with a servo controlling the flaperon position, and with the pressure scanner. The core element of the system is the computing unit which incorporates data handling SW engine providing communication with external devices. Moreover, it collects the data, provides system health/performance monitoring, and commands the driving units (DUs) to generate a control signal for its dedicated SJA. The SJAs can be operated in the open and close-loop. The close-loop feedback control is established with differential pressure sensor measurements utilized in CON5s. The sensors are placed in the trailing edge flaperons, i.e. behind the SJAs, and thus measuring their direct impact on the boundary layer behavior. In addition, for aircraft performance monitoring there were incorporated an air data computer (ADC) and a navigation unit (NAV). SJAs are further equipped with temperature and pressure sensors to ensure their operation safety aspects. The innovation consists in a time-sensitive control capability of DUs at the frequency of 1 kHz with high-power requirements. Each DU includes its own power converter at its input which adapts the input power into -180V and +180V voltage levels further used for the PWM. The power converter from the HW point of view was designed for a maximum average input power of 200W (+safety margin of 50W = 250W of max. continuous power input). However, it is capable of delivering greater power in the peaks, which is necessary to ensure sufficient quality of the SJA output signal regulation. If the power converter was permanently loaded with a higher power than 250W, that would have caused a risk of its damage due to high temperature. Thus, for its protection the power converter of the DU at its input uses a current limiter to ensure 25A maximal rating since there is no other input power limitation from the 28V on-board power source.

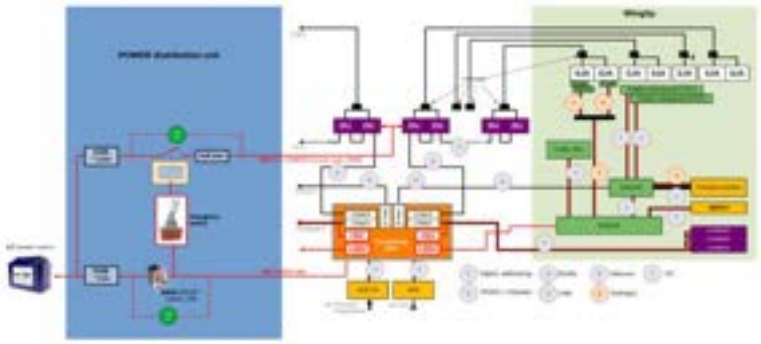


Figure1. *Principle scheme of the SJA assembly*

3. Results / Conclusions

Based on the tests already performed, the DU consumes only 50W when 170 Vp-p output voltage is applied on a pure C load. This value thus corresponds to the losses of the DU. It further leads to the assumption of maximal power which could be used for the SJA itself, i.e. approx.150W.

Based on performed measurements there was evaluated mean input power of 118W/SJA when 170Vp-p of the SJA driving signal was applied. It led to the estimation of the SJA consumption being just about 70W at maximum. Therefore, estimated maximal output power of 150W can be considered as sufficient for the application. The driving signal THD was confirmed to be < 1.5% of the driving voltage amplitude.

The DU itself incorporates protection against undervoltage, overcurrent, short circuit and overheat conditions. The design suffers from a high safety level due to an intention to be operated on the aircraft.

Wind tunnel test results of active flow control on an aileron

Julien Dandois, Colin Leclercq, Vianney Nowinski
ONERA, France

1. Introduction / Objectives

In the context of the FACLIFT project funded through the European Defence Fund (under grant agreement No. 101102557), this paper presents the results of the ONERA L1 wind tunnel campaign on the Pipistrel Vertical Solution (PVS) Virus wing equipped either with switching jet or with synthetic jet actuators. When an aileron is deflected above a certain angle, a separation appears on its suction side which decreases its effectiveness. Active flow control is a way to delay the appearance of this separation by injecting momentum in the flow and thus increase aileron effectiveness. The objectives of this campaign were:

- To investigate the performance of switching jets to control the flow separation on the aileron in an open loop manner both on the upper and lower sides
- To investigate the performance of synthetic jets to control the flow separation in an open and closed-loop manner only on the upper side of the aileron
- To gather aerodynamic data to identify an aerodynamic reduced-order model of a wing equipped with active flow control either by switching jets or synthetic jets in order to include this model in the design loop of an aircraft equipped with flow control actuators
- To test the electronics and actuators before going to flight tests

2. Methodology

Figure 1 shows a picture of the model mounted vertically in the L1 test section. The wing is tapered with no sweep. The mean aerodynamic chord is equal to 0.645 m. The reference area is chosen equal to 0.444 m^2 corresponding the area of the wing where the flow is controlled and not the full wing. The aileron chord length evolves from 15.6% of the mean aerodynamic chord at the root to 14% at the tip. The model span is 1.16 m.

The ONERA L1 wind tunnel is an atmospheric closed-loop wind tunnel whose test section has a diameter of 2.4 m and is operated at speeds ranging from 30 to 50 $m.s^{-1}$ (Mach number from 0.09 to 0.15) for this experiment. No transition trip has been applied to the model, as in flight. The model is mounted on a six-component balance below the wind tunnel which has

an accuracy of 0.1% of full-scale range. In addition, the model is equipped with one row of 32 pressure taps at mid-span.
The model is equipped either by seven switching jets (SWJ) which can blow on the upper or lower side of the model depending on the aileron deflection side or by seven synthetic jets (SJA) which can blow on the upper side only. The switching jets are 3D printed. Compressed air is supplied from outside of the model through the wing root. Hose forces due to the air supply pipes passing through the balance are mitigated by use of internal decoupling devices. The blowing mass flow rate was recorded thanks to a flow meter with an accuracy equal to 1% of full-scale range.

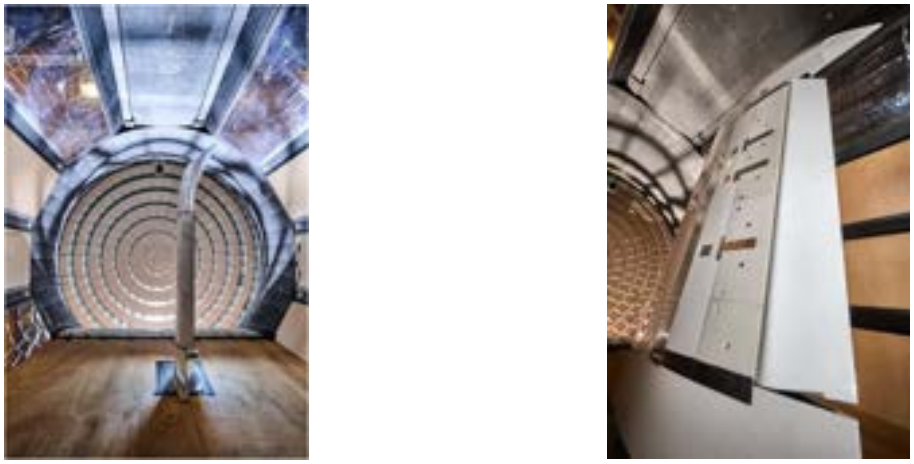


Figure 1. *Model in the ONERA L1 wind tunnel.*

3. Results / Conclusions

Figure 2 shows the effect of active flow control by SWJ and SJA on the lift coefficient. Without control, lift increases linearly between 0° and 10°. Then, a separation appears at the aileron trailing edge and lift starts to deviate from the linear curve. With control with SWJs, when the mass flow rate increases, the lift evolution becomes more and more linear up to the full reattachment around a mass flow rate of 19 $g.s^{-1}$. Above this mass flow rate value, we can observe an increase of lift even when the aileron is not deflected which means that we are in a circulation control mode. The maximum lift gain is equal to 63%. For flow control with SJAs (Figure 2 right), lift increase is smaller because the momentum injected in the flow is smaller than with SWJs. Nevertheless, SJAs are able to increase lift by 10% which is equivalent to flow control by SWJs with a mass flow of 12 $g.s^{-1}$. Closed-loop control with SJAs has shown that it is possible to keep the flow attached on the aileron at 30 $m.s^{-1}$ and 15° of aileron deflection while decreasing the power consumption by 80% compared to open loop control.

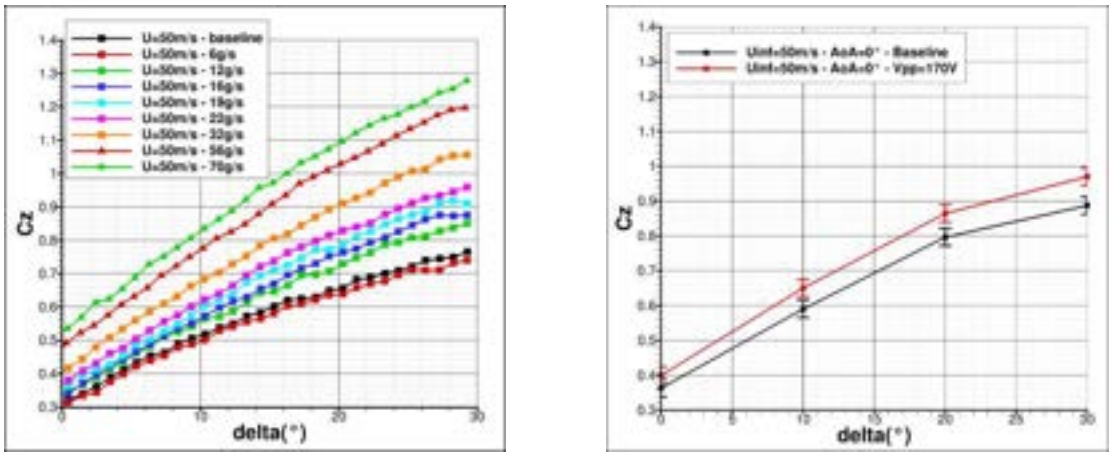


Figure 2. *Lift coefficient as function of aileron deflection (left: switching jets for different mass flow rates, right: synthetic jets).*

Flight Test Demonstration of Active Flow Control Using Switching Jet and Synthetic Jet Actuators for Control Augmentation and Drag Reduction in FACELIFT

Jernej Drofelnik[1], Luka Porenta[1], Julien Dandois[2], Colin Leclercq[2], Jan Rohac[3], David Ferris [4], Julien Weiss [5]

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[5] Berliner Institut für Technologietransfer GmbH, Germany

1. Introduction / Objectives

Active Flow Control (AFC) offers a route to augment conventional control-surface authority by manipulating the boundary layer, enabling reduced control-surface area for equivalent manoeuvre response and providing a practical pathway to drag reduction. European Defence Fund project FACELIFT (funded through grant agreement No. 101102557) addresses this challenge through two complementary AFC technologies, Switching Jet Actuators (SWJ) and Synthetic Jet Actuators (SJA), integrated for aircraft-level assessment.

A modified wingtip has been developed to integrate both actuator technologies and to enable their in-flight evaluation. Wind-tunnel campaigns informed the flight-hardware requirements and integration design, ensuring traceability from ground-based characterization to aircraft operation.

The flight-test campaign is currently ongoing and is planned to be completed by mid-summer. This work therefore emphasizes the aircraft-level integration approach and flight-test methodology that translate prior wind-tunnel findings into flight-relevant validation data.

2. Methodology

A dedicated flight-test article was developed to enable aircraft-level assessment of AFC technologies under representative operating conditions. The core element of this demonstrator is a redesigned wingtip, specifically developed to accommodate both SWJ and SJA, while preserving a conventional aileron-based control architecture. The wingtip design was driven by actuator integration constraints, aerodynamic requirements, and structural considerations, ensuring compatibility with both fluidic actuation principles and flight-test safety requirements.

The integration architecture combines pneumatic and electrical actuation subsystems with distributed sensing and data acquisition, enabling synchronized measurement of aircraft states, control inputs, and AFC system behaviour. The implementation builds directly on prior wind-tunnel campaigns, from which actuator operating envelopes, control strategies, and key test conditions were derived. This ensures traceability between ground-based characterization and in-flight evaluation, while extending validation to aircraft-level dynamics and operational constraints. Similar approaches to fluidic actuation and closed-loop AFC have been demonstrated in previous studies on active flow control systems , while jet-based flow control mechanisms have been extensively investigated and validated in aerodynamic applications .

The flight-test campaign is structured around repeatable manoeuvres designed to isolate the aerodynamic effects of fluidic actuation. These include steady flight segments and controlled lateral-directional excitations (e.g. roll inputs and roll reversals), executed in paired conditions with AFC inactive and active. This approach enables direct comparison of baseline and augmented behaviour, supporting the assessment of control-augmentation effects and identification of potential drag-reduction pathways through reduced control-surface deflection requirements. Both SWJ and SJA are evaluated using the same manoeuvres, A/B comparisons and assessment metrics, enabling consistent comparison of their impact under flight conditions.

3. Results / Conclusions

The FACELIFT programme establishes an end-to-end aircraft-level validation chain for active flow control technologies, combining wind-tunnel characterization, integrated flight hardware development, and in-flight experimental assessment. The aircraft used in the FACELIFT test campaign is depicted in Fig. 1. The redesigned wingtip demonstrator enables simultaneous integration of SWJ and SJA within a realistic aircraft configuration, providing a unique platform for comparative evaluation under flight conditions.

Wind-tunnel test campaigns have been successfully completed and have been used to define actuator operating conditions, integration requirements, and flight-test procedures. These results are currently being extended through an ongoing flight-test campaign, scheduled for completion in mid-summer, which is generating aircraft-level data under representative operating conditions.



Figure 1. *FACELIFT flight-test aircraft used for the AFC campaign.*

The adopted methodology enables direct comparison between baseline and AFC-augmented configurations, supporting the assessment of control-augmentation effects and the identification of potential drag-reduction pathways through reduced control-surface deflection requirements. Beyond aerodynamic performance, the campaign provides key insights into system integration, operational robustness, and measurement repeatability, which are critical for the practical implementation of AFC technologies in real aircraft environments. The experimental dataset generated within the flight campaign forms a basis for validation of numerical modelling approaches and supports the extrapolation of AFC effects to larger-scale aircraft configurations. In this context, the combination of experimental and modelling activities enables assessment of the potential impact of AFC technologies on aircraft-level performance, manoeuvrability, and design optimization when considered already in the early conceptual

Towards Practical Aircraft Applications of Active Flow Control: Aircraft-Level Trade-Offs and Integration Feasibility in FACELIFT

Miha Zupanič[1], Jernej Drofelnik[1], Julien Dandois[2], Colin Leclercq[2]
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[2]ONERA, France

1. Introduction / Objectives

Active Flow Control (AFC) has the potential to expand the aircraft design space by enhancing aerodynamic performance. Depending on the application strategy, AFC can increase maximum lift, improve control surface effectiveness, and reduce drag through improved lift-to-drag ratios. The European Defence Fund project FACELIFT (funded through grant agreement No. 101102557) investigates the aerodynamic impact and system integration requirements of two actuator technologies: Switching Jet Actuators (SWJ) and Synthetic Jet Actuators (SJA).

The aim of this work is to assess aircraft-level feasibility and determine whether current and near-term benefits of AFC technology can offset associated system penalties, such as added mass and increased power demand. The study focuses on practical application of the AFC technology on the main wing across two representative aircraft segments: lighter manned or unmanned vehicles up to 1 t MTOM, and heavier unmanned long-endurance configurations up to 13 t MTOM. Both retrofit integration into existing aircraft and implementation in new AFC-focused designs are considered.

2. Methodology

The methodology is based on a validation-informed design loop, where experimentally characterised actuator behaviour and known integration constraints are translated into reduced-order models suitable for aircraft conceptual design. The intention is to retain the key physical effects of AFC while making them usable within iterative aircraft sizing and trade-off studies.

First, both the aerodynamic effects of the AFC system and the associated system penalties (primarily mass and power demand) are integrated into a conventional conceptual design framework. The AFC models account for the main governing variables, such as freestream conditions, control surface deflections, and actuation intensity. At the same time, the system-level impact (particularly additional weight and power requirements) is introduced in a consistent way. This allows the design loop to directly evaluate how much aerodynamic benefit is achieved for a given system penalty. The setup is intended to support iterative sizing, trade-off analysis, and sensitivity studies, rather than single-point assessments.

In the second step, the approach is applied to a set of case studies focusing on the main wing. Both retrofit integration into existing aircraft and clean-sheet designs that can fully exploit AFC are considered. For retrofit cases, the design space is naturally more constrained, and the analysis focuses on how AFC can augment existing configurations. For new designs, AFC is included from the start, which allows greater flexibility in shaping the wing and control strategy. Across both cases, multiple design iterations are used to explore different integration concepts and to understand how AFC affects surface sizing, control authority, and overall aircraft performance margins.

Finally, the different configurations are assessed at aircraft level by varying key integration parameters. These include the choice of actuator technology (SWJ or SJA), actuation intensity, power source and distribution, and operational constraints. The resulting configurations are compared in terms of relevant aerodynamic outcomes, such as maximum lift, control effectiveness, and potential drag reduction. This provides a consistent basis for identifying where AFC integration is likely to be beneficial, and where system-level penalties become limiting.

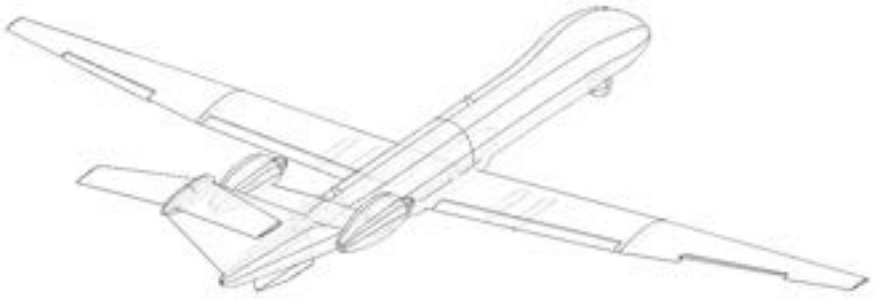


Figure 1. *Example AFC case study CAD model (unmanned long endurance aircraft).*

3. Results / Conclusions

Initial results suggest that AFC can reduce the required aerodynamic surface sizes, with corresponding improvements in aerodynamic efficiency. With the current technology, these benefits are more pronounced in the SWJ case, while smaller improvements are observed for SJA. Measurable gains are also evident in retrofit applications, although these remain smaller than for clean-sheet designs, where higher power allocation to AFC is possible. The effectiveness of AFC is strongly dependent on actuation intensity and, consequently, on aircraft-level power availability. However, diminishing aerodynamic returns are observed at higher actuation levels, particularly when accounting for additional system mass and power architecture demands. Comparisons between SWJ and SJA highlight trade-offs between aerodynamic effectiveness and integration complexity, underlining that AFC viability depends on balancing performance gains against system-level integration costs.

Space Technologies & Applications

Chaired by:
Prof. Gustavo Alonso (Universidad Politécnica de Madrid, Spain)

Development of an optimization model for fission-based space nuclear power systems

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Thales Alenia Space France, France

1. Introduction / Objectives

Fission-based nuclear power systems have been identified in the literature as a potential solution for future Lunar and Martian bases, as well as for robotic missions to the inner and outer solar system. This paper outlines efforts in modeling and optimizing a power conversion system and waste heat rejection using a nuclear heat source. In these models, newer options for heat exchangers have been considered, such as printed-circuit heat exchangers to further enhance performance. Most of this work has been based on studies conducted by Gallo and El-Genk nd Liu et al.

2. Methodology

To understand what options are available to get increased power outputs we started by making a trade study listing options for heat sources, power conversion schemes and heat rejection solutions and compared them using their TRL and relative masses and cost.
A more refined trade study was made comparing materials and subparts to be used for each option using relevant metrics such as density or thermal efficiency.
Following this, a simplified, spreadsheet-based model was built to simulate and compare Stirling and Brayton conversion cycles, estimating reactor, turbomachinery and radiator mass and performance as a function of rejection temperature.

A more detailed model and optimization program of a recuperated Closed Brayton Cycle and heat rejection system was subsequently developed in MATLAB and in Python. This model assumes an assembly using one radial compressor and one radial turbine stage, with a mixture of Helium and Xenon as a working fluid.
It gives information on turbomachinery heat exchanger and blade sizing and state variables of the working fluid at each step of the cycle, as well as sizing and performance of the heat rejection system.

3. Results / Conclusions

The study found that by offering significantly higher thermal efficiencies than static conversion schemes, dynamic conversion cycles allow much better scaling at higher power levels. Within our designated power range, a recuperated closed Brayton cycle (CBC) with noble gases as the working fluid, coupled to radiators employing a two-phase pumped fluid loop gives the best balance between technology readiness and specific mass. The heat rejection temperature, through radiator size and mass is the dominant part of the trade-off in optimizing such a system. Lastly, primary optimization results are in line with current research on the subject.

Development of a refractory tile for a reusable launcher

Marie Busquet, Marc Singlard, Julien Garcia
IRT Saint Exupéry, France

1. Introduction / Objectives

European launchers are currently fully expendable. Their re-use would provide greater operational flexibility while cutting launch costs. This re-use presents two technical-economic challenges: the recovery of the stage and its re-validation for the next flight.
Therefore, protecting reusable structures against thermal solicitation is a major challenge in the development of this strategy. Extremely high temperatures and heat fluxes are experienced by the structure, particularly during atmospheric re-entry.
Our work describes the development of a new thermal shield that relies on two temperature-management technologies:

- a thermal protection tile composed of a mineral insulator encapsulated within an oxide ceramic-matrix composite (O-CMC);
- a sol-gel coating (IRT SE patented formulation[2]) designed to strengthen the integrity of the O-CMC.

Compared with currently deployed solutions, this combination of technologies should achieve a steep thermal gradient while being cheaper than a refractory C/SiC tile (as used on the IXV[1]) and more durable than an ablative option made of cork.

2. *Methodology (up to 350 words)*

The manufacture of this new refractory tile is carried out in two distinct phases.
The first step involves preparing the oxide CMC material by impregnating oxide fibres with a metallic-oxide slurry and shaping them in a tile using dedicated moulds.
The second step consists of formulating the protective coating through the sol-gel process and then applied it by spray.
Because the O-CMC tile has limited high-temperature endurance, the sol-gel coating must improve its performance. In fact, it is a pre-ceramic metal-oxide coating that transforms into a crystalline state when exposed to high temperatures through a "ceramisation" process. This endothermic phase change allows it to absorb part of the heat flux, thereby providing thermal protection to the O-CMC substrate. Once ceramised, the coating continues to act as a passive thermal barrier to the substrate, exploiting the naturally low thermal conductivity of oxide ceramics.
To achieve our goal, an incremental iterative loop approach was implemented.

Study on O-CMC coupons

- Fabrication of representative CMC coupons of the outer skin,
- Application of the sol-gel coating at different thicknesses, with or without functional fillers,
- Multiple exposure to flame (methane/oxygen, 900 kW/m², 1600 °C) on the IRT SE test bench.

Study on tile

Once the optimisation work was completed, the best performing solution was transferred to the O-CMC tile and the developed thermal shield was also tested in flame test.

- Tile fabrication,
- Application of the optimised sol-gel coating,
- Multiple exposure to flame (methane/oxygen, 900 kW/m², 1600 °C) on the IRT SE test bench.

3. Results / Conclusions

The fire tests results on the untreated tile and for the sol-gel coated tile are shown in Figure 1 below.

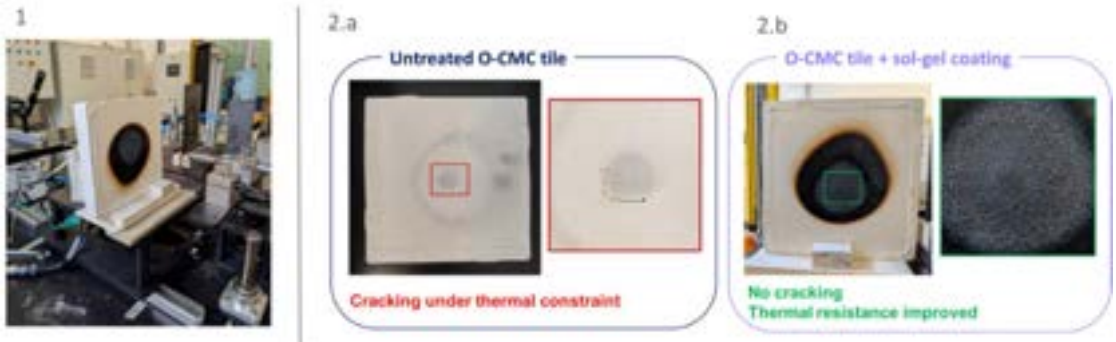


Figure1: *1- Flame test set-up and 2- Test results get after (a) untreated and (b) coated tiles exposure to a gas flame*

These tests demonstrate the benefits provided by the sol-gel layer. Indeed, the untreated tile cracks at the first flame solicitation (< 1 minute) whereas the coated tile retains its integrity (no visible cracks) after multiple flame solicitations.
Henceforth, the work will focus on tile refurbishment and on characterising this solution in more representative test environments and test methods.

Forecasting the Ionospheric Activity for Space Surveillance Purposes using Deep Learning Techniques

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1. Introduction

Among the major biases affecting the radar measurements in the service of low-Earth-orbit space surveillance are those induced by the ionospheric disturbances. To achieve sufficient tracking performance, it is necessary to correct these biases using models describing the evolution of these disturbances. Effective correction has been achieved through the use of vertical TEC (Total Electron Content) maps from multiple sources , which are available daily but with an average delay of two to three days. Leveraging an extensive TEC database and the recent advancements in prediction models suited for this technical issue , , this work aims to provide an accurate real-time and short-term forecasts of the ionospheric activity. These forecasts are specifically designed to support space surveillance radar systems in correcting the ionospheric disturbances. Therefore, the proposed approach aligns with the low-Earth-orbit radar-based space surveillance measurements and the accompanying operational needs of the Space Situational Awareness (SSA) domain.

2. Methodology

TEC prediction remains challenging as it is influenced by various factors of highly complex and nonlinear variations. The solar activity, the local time, and the sudden solar events (flares, coronal mass ejections, etc.) influence the TEC variations on a long-, medium-, and short-term scales, respectively. However, recent Deep Learning (DL) models have outperformed the empirical and statistical models, such as the International Reference Ionosphere (IRI) or NeQuick, in TEC prediction. From different neural network models which have been implemented for forecasting the ionospheric TEC activity , , we take a step further and work on improving the limitations of these models, refining it to fulfill our vertical TEC maps dataset.
In the view of its scientific reputation regarding the high accuracy of a non-IGS product and of its encouraging performances in estimating the ionospheric Doppler velocity in low-Earth-orbit targets' measurements , we chose the UQRG vertical TEC maps, provided by the Universitat Politècnica de Catalunya (UPC), as a valuable input dataset for this work (see Figure 1). Indeed, UQRG maps compensated almost 80% of the Doppler velocity errors in radar measurements over the high-solar-activity period from September to December 2024 .

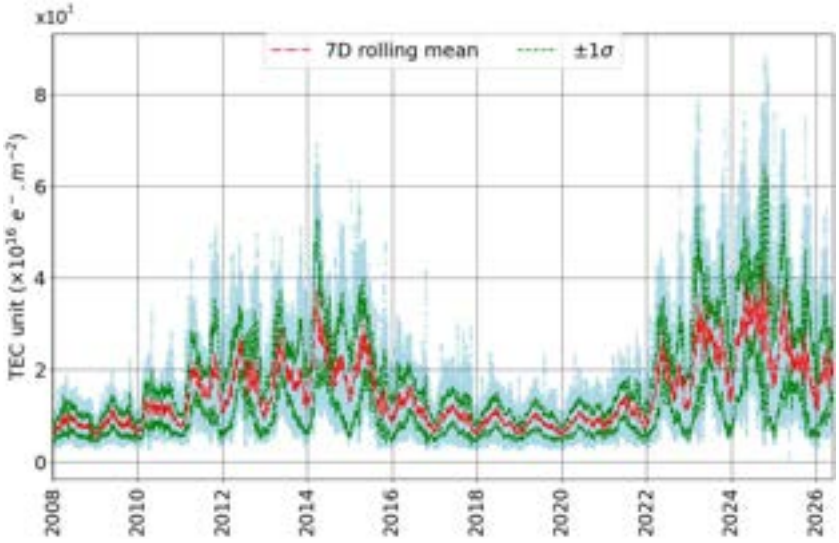


Figure 1. *UPC vertical TEC data above [lon: 0°; lat: 42.5°] from January 2008 to May 2026.*

3. Results

Our proposed prediction model includes an Encoder-Decoder Self-Attentional Convolutional Long Short-Term Memory (ED-SA-ConvLSTM) architecture , integrated with external physical parameters that govern the ionospheric dynamics . Combining both, the spatio-temporal feature extraction capabilities of a traditional ConvLSTM with the long-range memory of a Self-Attention Mechanism (SAM) module, and an Encoder-Decoder structure for unequal input-output lengths with physical parameters (such as the geomagnetic indices A_p and the solar radio flux $F_{10.7}$), our framework aims to outperform state-of-the-art benchmarks such as the Center for Orbit Determination in Europe (CODE)'s one-day prediction (c1pg) and the standard ConvLSTM models. We can further compare the SAM module in with the residual connection strategy adopted in to allow for a more refined and stable prediction model.

Multidisciplinary Conceptual Design Framework for Reusable Space Vehicles with Re-Entry and Servicing Capability

Iara Figueiras, Girolamo Musso, Alain de Souza, Frederico Afonso, Fernando Lau
Instituto Superior Técnico, Portugal

1. Introduction / Objectives

The rapid expansion of the global space industry has driven an increase in launches, raising concerns about environmental impact and growing space debris. Meeting these challenges might demand a new generation of reusable, multipurpose space vehicles and design tools capable of assessing their performance, reusability, and environmental impact from the earliest design stages. This work extends an in-house low-fidelity design framework, originally developed in MATLAB® for sounding-rocket conceptual design, toward the conceptual and preliminary design of a reusable multipurpose vehicle aligned with the New Space Portugal agenda . The target concept is sized to fit within a launcher payload fairing and is intended

to deliver payloads to specific orbits, perform orbit-change maneuvers enabling in-orbit servicing, and return through atmospheric re-entry for recovery. The primary objective is to support early-phase engineering decisions through this unified, decision-oriented methodology.

2. Methodology

The framework couples several disciplinary modules into a single conceptual-design environment. Current maturity includes geometry parameterization, aerodynamic coefficient prediction, trajectory propagation, aerothermal load estimation, Thermal Protection System (TPS) modelling (see Figure 1), and multi-objective optimization using both genetic and gradient-based methods . This baseline already enables trade-space exploration across competing design objectives.

The next development step focuses on two mission-critical additions. First, reusability is addressed through and improvement to the TPS module: a transient multilayer thermal response model has been implemented using a one-dimensional finite-difference scheme to capture in-depth heat conduction during entry. Building on this thermal solver, reusability and ecodesign indicators are being developed: a discrete architecture classification (reusable vs. ablative-based) and a continuous thermal-margin factor that quantifies the normalised distance to each material's temperature limit, the latter feeding the optimization loop as a constraint. A traceable material inventory, structured as a bridge towards a future life-cycle assessment, complements these indicators. The TPS module is designed to extend to actively-cooled metallic architectures, broadening the trade space beyond passive reusable and ablative concepts. Second, orbital mechanics capability will be integrated to model ΔV-constrained transfers for satellite delivery and in-orbit servicing.

Multidisciplinary optimization runs are planned, beginning with the formal construction of the optimization problem (design variables, objectives, and constraints). Comparative studies will support validation and verification against reference cases, while parametric studies will examine how key design parameters affect re-entry loads and overall feasibility. Later in the process, life-cycle considerations are introduced at concept level to enable early-phase ecodesign assessment of next-generation space vehicles.

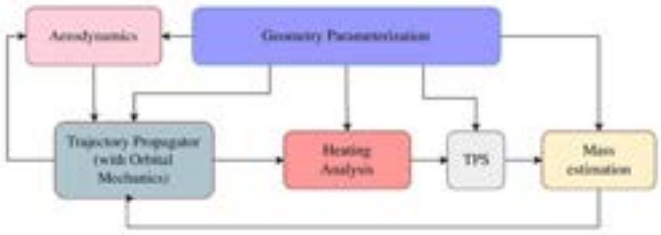


Figure 1. *Modules of the MATLAB framework.*

3. Results / Conclusions

The extended framework provides a decision-oriented methodology for the early-phase ecodesign of next-generation reusable space vehicles by coupling mission performance,

TPS-driven re-entry feasibility, orbital manoeuvrability for servicing missions, and life-cycle considerations at concept level. Expected outcomes include validated TPS transient thermal responses, and trade-space maps relating design parameters to re-entry loads and ΔV budgets. By bringing reusability and environmental criteria into the conceptual phase, the framework supports more informed early engineering decisions. The approach is broadly transferable to other reusable launch and servicing vehicle concepts within the emerging European New Space ecosystem.

Visibility-Constrained Pruning for Rapid Tasking in LEO Earth Observation Constellations

Yifan Cai, Camilla Colombo
Politecnico di Milano, Italy

1. Introduction / Objectives

Dynamic, unpredictable ground conditions heavily demand rapid responses in modern Earth Observation (EO) operations. LEO constellations offer a fast solution . Routing commands from Ground Stations (GS) via Inter-Satellite Links (ISL) to executing satellites, however, introduces a highly complex, multi-hop node optimisation problem. Rarely can conventional strategies handle this well. Plagued by the combinatorial explosion of vast search spaces, these older methods suffer from severe computational complexity and lengthy solution times, which ultimately blocks real-time emergency responses.

This study introduces a unique, physics-constrained heuristic method to minimise command-to-observation latency efficiently. Our core innovation is bold. By reversing the traditional "network-first" paradigm, the proposed framework utilises absolute timeline visibility gating—inherent to EO models—to filter out unfeasible communication routing options completely. Consequently, the overall computational complexity drops significantly while urgent sensor tasking remains entirely dependable.

2. Methodology

The methodology models a high-fidelity LEO constellation comprising *N* satellites, a ground station network, and specific EO targets. The core analytical approach shifts from a pure graph-theory multi-hop search to a mission-driven chronological pruning strategy.

Traditionally, finding the optimal command path involves exploring an exponentially growing multi-hop space from the GS to all potential satellites. Instead, this framework constrains the search space by integrating target visibility models. The optimisation is simplified into the following sequential algorithm:

First, orbital mechanics models pre-calculate the visibility windows for all *N* satellites over the specified ground target. These feasible observation nodes are then sorted chronologically on an absolute timeline to identify the earliest potential observer. Secondly, for the first available satellite on this timeline, the algorithm evaluates the preceding communication topology. It checks if a valid multi-hop ISL path from the GS to this specific executing satellite exists prior to the observation epoch.

If the antecedent communication pathway is unobstructed and valid, the task is successfully added to the planning schedule. If the path is unfeasible (due to lack of GS contact or broken ISL topologies), the algorithm discards this node and proceeds to test the

communication feasibility for the next earliest visible satellite. This sequential verification continues until a viable observer-communication pair is found.

3. Results / Conclusion

Simulation results demonstrate that the proposed chronological pruning strategy reduces computational time by several orders of magnitude compared to traditional exhaustive multi-hop routing algorithms. By strictly evaluating preceding communications only for satellites already verified as visible, the algorithm successfully bypasses millions of unfeasible routing combinations without sacrificing the minimal response time required for emergency tasking. To illustrate the practical output of this efficiency, Fig. 1 displays the comprehensive schedule generated for all 100 dynamic disaster scenarios, showing successful task allocation across the operational timeline.

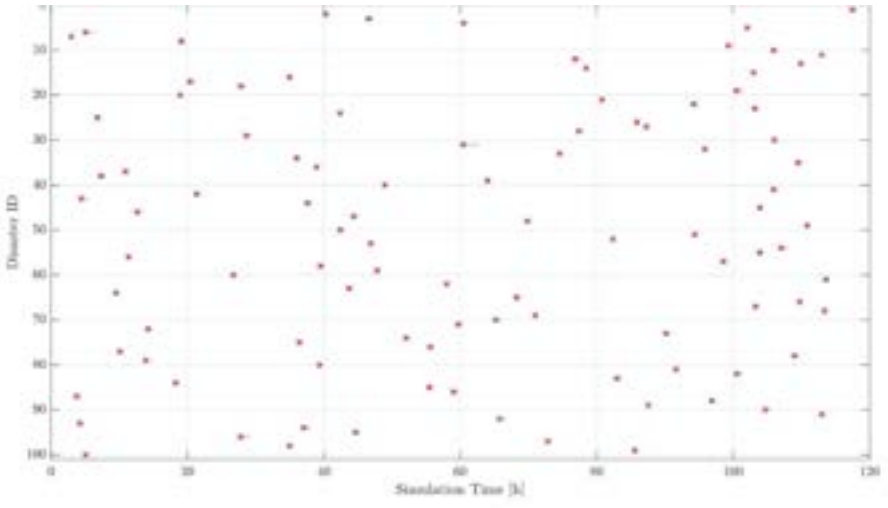


Figure 1. *Complete scheduling results for the 100 simulated disaster scenarios. The horizontal axis represents simulation time, and the vertical axis lists individual task IDs, demonstrating full coverage and timely allocation of all emergency requests.*

In conclusion, integrating orbital visibility constraints directly into the communication routing logic provides a highly efficient and scalable tasking algorithm for large-scale LEO constellations. This approach ensures rapid and sustainable sensor tasking for next-generation Earth Observation networks, significantly enhancing the operational viability of dynamic monitoring systems and disaster response payloads.

Digital Engineering for Aerospace Systems

Chaired by:
Dr. Carlos Cabaleiro de la Hoz & Mr. Francesco Torrigiani (German Aerospace Center (DLR), Germany)

Accelerating the Development of Hybrid-Electric Regional Aircraft: a SysML v2 Environment for Digital Design and Verification

Francesco Torrigiani[1], Jasper Bussemaker[1], Sparsh Garg[1], Carlos Cabaleiro[1], Fabien Retho[2], Olexiy Kupriyanov[2], Klara Ziegler[2], Juan Manuel Lorenzi[2], Jean-Marie Gauthier[3], Jean-Christophe Giret[3], Vito Primavera [4]

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[2] Siemens, Germany
[3] IRT Saint-Exupéry, France
[4] EnginSoft, Italy

1. Introduction / Objectives

Hybrid-Electric Regional (HER) configurations imply far higher complexity than conventional configurations while involving new aircraft technologies and broader collaboration across the value/supply chain. The limitations of the State-of-the-art digitalization techniques put at risk the achievement of the 2035 Entry-Into-Service target. Objective of the Clean Aviation ODE4HERA project is to accelerate the development of Hybrid-Electric Regional Architectures by combining existing technologies for Model-Based Systems Engineering (MBSE), Multidisciplinary Design Optimization (MDO) and Product Lifecycle Management (PLM) into an Open Digital Platform and extend them with novel open interfaces, formats and data transformation technologies.

2. Methodology

This paper presents the blueprints of the Open Digital Environment developed within the ODE4HERA project for the design and verification of Hybrid-Electric Aircraft. Key elements of the digital environments are the Platform Solution-Neutral Architectures (SNA) and the Ontology Basis for development of HER configurations. The Solution Neutral Architecture (SNA) provides a detailed description of the modules composing the entire Open Digital Platform, the functions fulfilled by each of the modules and the data exchange among them. The Ontology Basis for Hybrid-Electric Regional Architectures (HERA Ontology), which is based on the semantics of the second version of the System Modelling Language (SysML v2) and practically consists of a SysML v2 application library extending the standard library. In addition to ensuring consistency and interoperability, the HERA Ontology allows for an efficient implementation of the platform modules network. There is no more need for development of specific module-to-module interfaces. A single interface with the common data-structure enables the integration of the module at hand in the ODE4HERA platform, reducing implementation and maintenance effort. By relying on the well-structured SysML v2 extension mechanism, the HERA Ontology guides the development of new ODE4HERA platforms modules. Domains not covered by the current version of the HERA Ontology can be modelled in SysML v2 and the associated SysML v2 interfaces developed to integrate the new module in the ODE4HERA platform independently of the other modules already composing the platform.

The HERA Ontology does not have the purpose of representing the complete database generated throughout the entire development, but instead includes only the data sets relevant for enabling interconnections among the different steps of the process and the associated authoring tools. The link between the HERA Ontology and the different standards already available and well established in the aeronautical context is key for fostering the adoption of the ODE4HERA methods and tools in the wider aeronautical community. In the paper, the link with the Functional Mock-up Interface (FMI) for time-domain simulation and

the Common Parametric Aircraft Configuration Schema (CPACS) for aircraft design is described in details and explained with specific examples.

3. Results / Conclusions

The design and verification of the thermal management system (TMS) for a hybrid-electric powertrain system is presented highlighting the advantages provided by the developed approach.

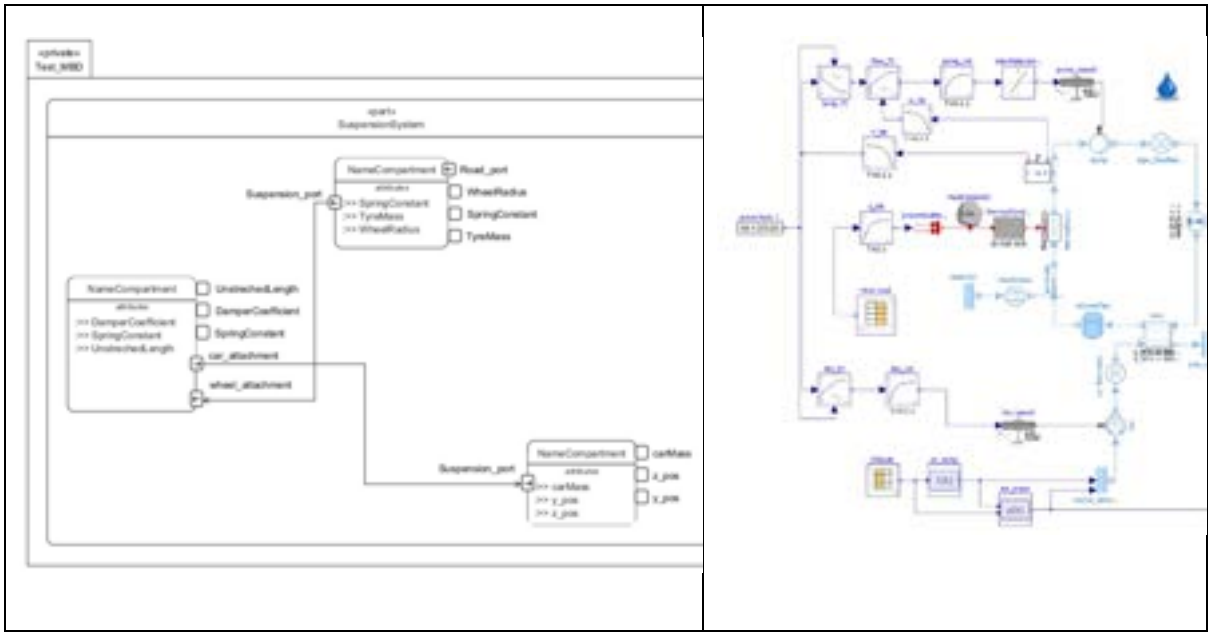


Figure 1. *Supporting material for the paper will include images of the corresponding models (SysML and TMS example), as this one as an example*

Open Digital Platform: Connecting multiple domains and tools to support Digital Engineering Workflows

Fabien Retho[1], Klara Ziegler[1], Elias Allegaert[1], Olexiy Kupriyanov[1], Philippe Barabinot[1], Sparsh Garg[2], Jasper H. Bussemaker[2], Vito Primavera[3], Andrea Terracciano[4], Pierpaolo Borrelli[4]

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[3] EnginSoft, Italy

[4] Leonardo, Italy

1. Introduction / Objectives

Aircraft development relies highly on simulation involving different domains and tools. An Open Digital Platform (ODP) to enable collaboration between different stakeholders and tools is developed within the Clean Aviation ODE4HERA project **Error! Reference source not found.**. A first version of the ODP was developed using solution neutral ontologies as data structure **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**. This article will present the ODP evolution from its first release to the latest one. The ODP main features will be described and compared with the needs and

requirements expressed to support Hybrid Electric Aircraft research and design. With one or multiple workflows and a set of tools, it is possible to create an ODP instance. In the article, the focus is on an instance developed in the ODE4HERA context. This instance includes Model-Based Systems Engineering (MBSE) capabilities with domains such as Model-Based Design (MBD), Multidisciplinary Design Optimization (MDO), Simulation Process and Data Management (SPDM) and Product Lifecycle Management (PLM).

2. Methodology

The ODP instance proposed in this article is an illustration of how an ODP instance can be set up and used. This instance will be used also to allow the presentation of main features. The instance proposed in this article is built around a workflow supporting design via aircraft requirements validation and usage in design.

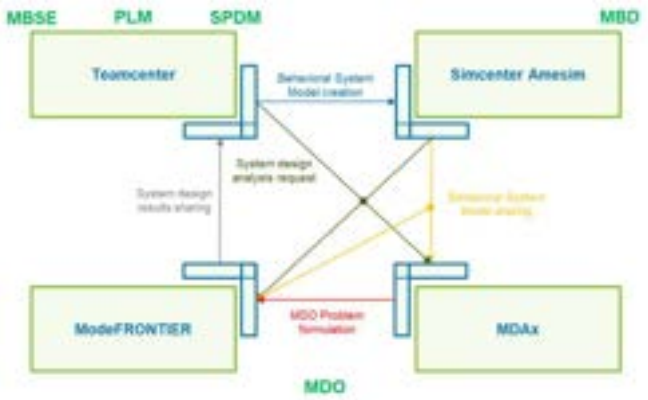


Figure 1 : *ODP Instance* 1: Workflow, tools and domains

Figure 1 is showing the ODP instance's four tools and five domains. This figure illustrates all the exchanges between tools which represent the main steps of the workflow, from requirement selection, behavioral model creation, its usage in an MDO problem and through to results being fed back to the design. Based on this instance, the tools and following the workflow steps, several ODP's main mechanism and features will be explained and highlighted: Usage of SysML V2 based ontology**Error! Reference source not found.**, connectors to be defined for each tool, data and information exchanged, flexibility, openness, traceability. In a dedicated section, an example based on a real industrial Hybrid Electric Regional Aircraft (HER A/C) will be used to illustrate the usage and also used to verify and validate the platform. This example will open the discussion on the ODP roadmap and next steps, driven by aircraft designers (end-users) of the platform.
A pros and cons analysis will be proposed to finish this technical part, including main important items already developed and highlighting the ones on the roadmap, already presented after the industrial example.

3. Results / Conclusions

This article summarized the evolution of the ODP, its development, and explain all its specificities which are justified by its end user orientation. The article is presenting one of two

instances proposed in the context of ODE4HERA project in order to link it with real industrial development. The latest platform version proposed with ODE4HERA is completed by a roadmap to open possible future evolution and flexible future usage.

A Git-based Collaborative Engineering Platform for MBSE using SysML v2

Jasper H. Bussemaker, Carlos Cabaleiro, Jonas Jepsen, Marko Alder, Sparsh Garg, Marcel Mischke, Aprajita Kain, Erwin Moerland, Luca Boggero, Björn Nagel
German Aerospace Center (DLR), Germany

1. Introduction

SysML v2 is an industry-backed Model-Based Systems Engineering (MBSE) language which next to graphical notation also supports textual notation . Defining the systems models in text enables the use of the Git version control system for data exchange, versioning, and collaboration.
This paper presents a collaborative engineering platform built around SysML v2 and Git. It supports the integration of authoring and analysis tools and synchronization between SysML v2 and domain-specific models. It also provides various automation steps such as syntax checking and documentation generation.
By integrating dedicated authoring tools, systems engineers have access to modeling environments for MBSE and Multidisciplinary Design Analysis and Optimization (MDAO) activities, such as structured requirements modeling, system architecture optimization, and multidisciplinary evaluation. We will demonstrate that the platform together with integrated authoring tools provides a convenient, integrated modeling environment for systems engineers to develop new complex aerospace systems.

2. Methodology

SysML v2 is the newly released second version of the Systems Modeling Language (SysML), which has many improvements over prior versions , such as formal semantics, new language extension mechanisms, and graphical and textual notations. The textual notation allows the storage, exchange, management and versioning of systems models using Git, a version control system widely used in software engineering. By using Git, the aerospace engineering domain can start applying ways of working and lessons learned from decades of experience in software engineering.
To enable the integration with all engineering disciplines needed for developing a complex system, in particular through MDAO techniques, the platform also supports domain-specific modeling formats. Due to partial overlap in modeling concerns and traceability from systems models to domain-specific models, the platform provides a comprehensive synchronization concept and implementation. One of the supported domain-specific formats is CPACS , a standardized format for storing aircraft design data, in which for example the top-level aircraft requirements are synchronized with requirements defined in SysML v2 models.
To improve automation and ensure model quality, the platform implements several model processing functionalities in the form of Continuous Integration (CI) jobs, that are automatically triggered upon certain repository events such as pushing model updates or requesting the merger of two branches. The currently implemented functionalities are: model syntax and completeness checks, requirements satisfaction checks, automatic generation of documentation, and model deployment for reuse in other systems engineering projects.
Finally, the platform will provide users with a web-based dashboard, where they can view

information about the repositories (for example, documentation and automation status), where they can view and edit models, as well as launch authoring tools that are connected to the platform. The final paper will introduce all of the functionalities provided by the platform, as shown in Figure 1, in more details.



Figure 1. *Overview of the collaborative platform, with a central Git repository for storing models, and various tools for authoring and automation.*

3. Conclusions

The final paper will present a Git-based collaborative digital engineering platform for developing complex systems using SysML v2 and extended by domain-specific models. The platform provides various functionalities for enabling collaborative complex systems engineering, including model synchronization, model checking and deployment automation, automatically generated project documentation, and a project dashboard. In future work, the platform will be used in realistic application cases and further improved based on user feedback. Planned developments include integrating more authoring tools covering more steps of the systems design process, the development of uncertainty quantification capabilities, and the application of artificial intelligence to support and potentially automate various steps in the product development process.

Integration of Model-Based Design and Surrogate-Based Multi-disciplinary Design and Optimization into a Dynamic Simulation Framework for Thermal Management Systems

Andrea Mameli[1], Francesco Torrigiani[2], Sparsh Garg[1], Nicole Viola[2], Carlos Cabaleiro de la Hoz[2]
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[2]German Aerospace Center (DLR), Germany

1. Introduction / Objectives

Civil aviation industry is increasingly focused on reducing climate and environmental impact. Novel More-Electric Architectures (MEAs) can reduce fuel combustion and, consequently, pollutant emissions. These architectures, entail electrifying on-board systems while reducing or removing pneumatic, mechanical and hydraulic systems . A subset of MEAs includes Hybrid-Electric Architectures (HEAs), where propulsive power is provided by the combination of electric motors and internal combustion engines . HEAs present a major technological

challenge: thermal management. As higher powers are required, more heat is produced, hence requiring efficient Thermal Management Systems (TMS). Current studies existing in literature employ a conventional approach of an MBD (Model-Based Design) - MDO (Multi-disciplinary Design and Optimization) workflow , based on static simulations. However, static simulations can't highlight common behaviours of complex systems as cycles, saturations or load and environment variations. This study aims to overcome the limitations in existing research by introducing dynamic simulations within the MBD-MDO framework, thus improving the accuracy and completeness of results.

2. Methodology

The proposed methodology is divided in two main blocks: MBD and MDO. In the MBD block, five TMS architectures found in literature (i.e.) are built in Modelica language , with OpenModelica libraries and Thermofluid Stream library . The five architectures are built starting from a common main coolant loop and then other loops/branches/components are added. Then, models are validated and simulated in a time-dependant domain with variable external environment and heat loads, resulting in a dynamic simulation. The use of dynamic simulations is justified by the need of analysing the real-world behaviour of those critical systems, addressing all possible related issues. Static simulations, the most done in literature , do not cover all the possible issues that a robust TMS must address, like instantaneous peaks or limit cycles. The outputs of the dynamic simulations are then used for determining through scaling laws e.g. the total mass and peak electrical power of the system. The second block of the methodology is related with the formulation and execution of MDO workflows. To pursue execution speed and reduce computational cost, surrogate functions for objective variables are used in optimization instead of the actual models. Given the same inputs as simulations, surrogate functions can represent simulation outputs with high reliability . These functions enable easier optimization processes in terms of problem definition and computational cost . Surrogate functions need DOEs to be built . A first DOE is used to explore the design space and train a PoV (Probability of Viability) surrogate function . PoV functions help in predicting whether an area of the design space will produce an unfeasible (failed simulations due to numerical errors or out-of-bounds control values, in literature "hidden constraints") or a feasible design point without performing any simulation. PoV function is then used to filter, out of a larger pool of candidates, feasible design points for a second DOE. Owing to its higher number of feasible points compared to the first DOE, this DOE is employed to train surrogate models for the objective variables. Optimization is finally performed on surrogates: a Pareto front is obtained and then filtered by re-simulating all the Pareto points, assessing surrogate prediction error and discarding Pareto points with high relative error.

3. Results / Conclusions

The aim of this research work was integrating dynamic simulations within an MBD-MDO workflow. Two main problems arose from dynamic simulations integration: hidden constraints and high computational cost. The main novelties brought by this work are therefore the integration of dynamic simulations and the application of countermeasures required by these hurdles:

1. PoV function to address hidden constraints: feasible points increased from 18% in the first DOE to 67% in the second PoV-driven DOE (as shown in Figure 1);

2. Surrogate functions to reduce computational cost: computation time reduced from hours to minutes.

Finally, a Pareto front is produced, as represented in Figure 2. It is then filtered, yielding 10–50 validated optimum points that minimize total system mass and peak electrical power. The proposed methodology provides a stable, fast and reliable design and optimization workflow that reduces total system mass by 15% and peak electrical power by 9%. Thereby, better TMS designs are possible, advancing hybrid-electric architectures development.

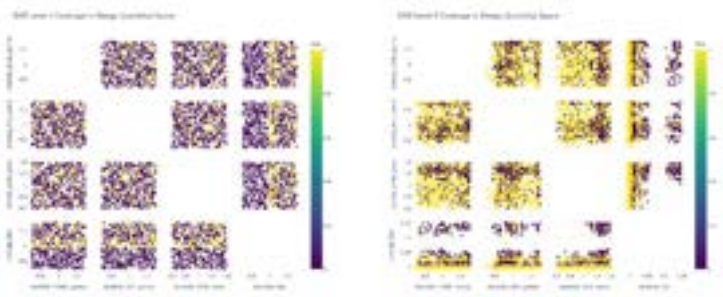


Figure 21. DOE 1 (left) and DOE 2 (right) feasible (yellow) and unfeasible (purple) points

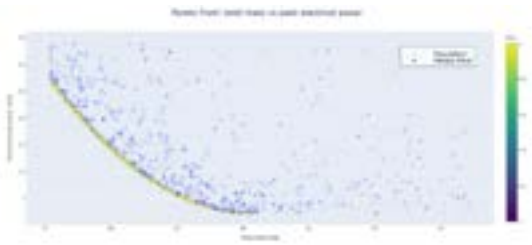


Figure 2. Pareto front

Acknowledgement: The research presented in this paper has been performed in the ODE4HERA (Open Digital Environment for Hybrid Electric Regional Architectures) project and has received funding from the European Union Clean Aviation Joint Undertaking under grant agreement n° 10114051.

Integrated digital platform for aircraft engine's parts life cycle management

Jakub Broniszewski, Katarzyna Frydrycka-Zabadaj, Dariusz Oracz
GE Aerospace, Poland

1. Introduction

The aim of the project was to develop a digital platform to support the aerospace life cycle management process, starting from airfoil design up to tracking parts in the field. The three main modules include: Module A – fluid-structure interaction analysis with mechanical nonlinearities, Module B – forecasting operating costs, and Module C – operational and durability analysis. In Module A, the use of the Hybrid Frequency-Time Domain Method (HFT) allows analysis of parts with no well-defined dynamic mechanical boundary. Module B utilizes Natural Language Processing (NLP) with a down-selected Multinomial Naive Bayes (MNB) model to classify each service event. Data flow was automated, and a centralized database was created to collect information from multiple sources. The Flight-by-Flight (FbF) method used in Module C overcomes the limitations of the classical "mean" method in describing nonlinear damage accumulation and interactions between explanatory variables. All results show good agreement with validation data.

2. Methodology

FSI analysis used in the process involves in-house tools for CFD with morphing capability and mechanical analysis. A Reduced Order Model (ROM) for the structural part was used to reduce calculation time. The Unsteady Reynolds-Averaged Navier-Stokes (URANS) solver communicates with the HFT solver via hierarchical data format (HDF) files. Alignment quality was identified as a critical parameter for data exchange between the surface grids. The Radial Basis Function (RBF) algorithm was parallelized and optimized to handle the large data sets used for mapping. To excite the ROM model, a vector of modal forces was calculated, including all modes used to construct the reduced model. The process involving the CFD solver with grid morphing and the mechanical solver was run in a loop until the convergence criterion was met. As a result, the vibration amplitude and stress field were obtained.

Module B was developed to provide software for monitoring and predicting costs associated with the operation of engines under long-term service contracts. A dedicated database environment was created as a single, robust source of operational, maintenance and repair data, supported by transactional mechanisms. On this foundation, interactive dashboards and analytical services were built, including a machine-learning classifier of scrap reasons and a repair-cost monitoring component with automatic trend detection. For cost prediction, several model families were evaluated, and although alternative approaches such as linear models, polynomial regression, decision trees and neural networks were considered, tree-based methods proved most suitable given the relatively small dataset. A Random Forest model was ultimately selected. All functionalities are exposed via a web service.

Building on detailed business requirements and an assessment of current predictive capabilities at fleet and engine level, module C introduces advanced flight-by-flight (FbF) severity modelling and Weibull anchoring methods to enhance engine life and cost prediction. The FbF framework was extended with severity functions, parameter constraints and statistical tests, as well as tools for model comparison and emerging cross-validation. These enhancements delivered significant gains in predictive quality versus baseline methods.

3. Results

Results from the FSI process show good agreement with test data obtained for fan and inlet guide vane (IGV) airfoil. The automated process allows quick and robust numerical testing of parts under development.

The developed platform also contains two complementary modules within an automated, end-to-end workflow supported by a centralized database. Data ingestion, preprocessing, model execution, and result reporting were streamlined to minimize manual intervention and ensure consistency across fleet, engine, and component levels. The central data repository aggregates information from multiple sources, enabling robust analytics, traceability, and efficient maintenance of predictive models. Both the cost-forecasting and flight-by-flight durability methods were validated against reference and operational data, showing good agreement and exceeding predefined predictive accuracy targets. This confirms that the automated, data-driven approach reliably supports aerospace life cycle management decisions.

How to improve the "Digital Assistant (DA) – Pilot interaction" design process

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1. Introduction / Objectives

Artificial Intelligence (AI) applications are increasingly finding their way into flight automation in the form of Digital Assistants (DAs). DAs are intelligent software applications or systems which can give advice and sometimes can autonomously handle human tasks. When such DAs are developed to reach high maturity levels, they can support pilots in task execution, thereby reducing workload. Safety must be ensured while using DAs in flight operations. For the success of a DA, one needs to know how the DA fits in with the tasks that pilots have to execute. So, early in the design consideration and development process it is essential to identify how and when the DA should function and support the pilots in carrying out their tasks without compromising safety. The current study explores the need and presents the idea of early identification of safety implications with the use of an DA in execution of pilot tasks.

2. Methodology

The design of a DA was evaluated through a case study. Selected in the study is a DA that has been recently developed within the framework of SESAR-funded project JARVIS - Just a rather very intelligent system . The DA application features a capability for predicting arrival route and runway (Figure 1) most likely to be used for the time of arrival at an airport. Such a DA can support pilots in preparing the landing in early stage of flight prior to obtaining information and instructions for approach. It can also contribute to manage efficiently Reduced Crew Operation (RCO) e.g. in case of pilot incapacitation. Further selected in the case study is the arrival trajectory to a large international airport with multiple runways. Amsterdam Schiphol Airport was chosen due to its operational complexity and number of combinations for runway preferences (Figure 2). The pilots' tasks for the flight phases including level flight, descent, approach and landing were analysed and verified for their criticality and associated safety impact. For the task analysis an experienced pilot and a human performance expert as Subject Matter Experts (SMEs) were engaged to go through the pilots' tasks in a normal Two Crew Operation (TCO) setting. A simplified hierarchical task analysis (HTA) technique was applied to elucidate the task structure, and navigation charts were employed to obtain insight into the pilots' tasks and their criticalities, interaction between pilots, and communication between pilots mutually and between pilots and air traffic control (ATC).

In addition, a number of activities were carried out to get a better understanding of the pilots' tasks and the DA design. A Flight Crew Operations Manual (FCOM) for a large commercial jet was consulted to capture the chronology of pilots' handling of tasks and communication; an experienced test pilot was interviewed to obtain his opinion about the preliminary design and use of DAs in the cockpit; and a brief analysis of a number of JARVIS documents with technical specifications and operational requirements related to the DA feature for predicting arrival route and runway was conducted.



Figure 1. *Illustration of JARVIS airborne digital assistant (AIR-DA) feature "Arrival and runway predictions".*

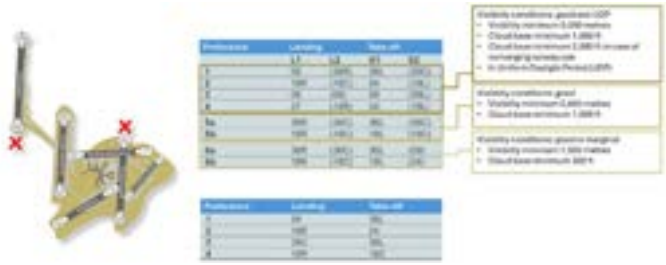


Figure 2 *Amsterdam Airport, runway preferences between 06:00 and 23:00 (upper right) and 23:00 and 06:00 (lower left).*

3. Results / Conclusions

For working with a DA, errors made by the pilot and or DA should be avoided as much as possible. Pilot errors could eventually lead to safety concerns. The case study demonstrated that workload can be more evenly distributed over the flight. Namely, the pilots can start preparing their landing at the – low workload - cruise phase of the flight so that they can operate more effectively during the more task-demanding approach and landing phases. The study also showed that the DA ideally is not used during high task-demanding phases of the flight. System developers of DAs could benefit from an early identification and analysis of safety implications to help improve or refine the DA design such that the usability can be increased. Also, the system developer could increase the DA usability by improving the functionality and designing training and procedure in use.

Application of Open Digital Platform to the Design and Verification of Hybrid-Electric Regional Aircraft

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1. Introduction / Objectives

The design of Hybrid Electric Regional (HER) aircraft is highly challenging due to the complexity and high integration of their systems, resulting in time- and cost-demanding verification and validation processes that hinder early error detection and efficient model integration, requiring user interaction with an effort proportional to the data flow. To address these issues, the ODE4HERA project is developing an Open Digital Platform (ODP) connecting engineering domains through an interoperability modeling language and novel open interfaces **Error! Reference source not found.**.
This paper presents the application of the ODP to the integrated design and Virtual Verification and Validation (V&V) of HER vehicles. By deploying the platform throughout the development process, this study demonstrates the ODP's capability to synchronize key domains, including Model-Based Systems Engineering, Model-Based Design, Multidisciplinary Analysis and Optimization, Product Lifecycle Management, and Simulation Data Management. The results provide a quantitative assessment of the platform's impact on design efficiency and consistency.

2. Methodology

This work extends the results presented in **Error! Reference source not found.**: while the previous study evaluated the impact of ODP mainly on the Multidisciplinary Analysis and Optimization module, with the other design activities performed using standard industrial practices, here the entire ODP workflow is considered. The study therefore addresses the full design process covered by the ODP and summarized in figure 1 together with the tools



adopted in each phase.

Figure 22. *Virtual Integrated Verification and Validation process and adopted tools.*

The proposed application case enables a more comprehensive assessment, as it is based on an extended System of Interest (SoI) of the Ultra Efficient Regional Aircraft (UERA) configuration developed within the HERA project. In detail, the aircraft presents two parallel hybrid power plants having thermal engines and electric motors in a parallel layout. The SoI is composed of the main aircraft systems, including hybrid propulsion, power sources, electrical distribution with smart energy management, fuel system, and thermal management system. The related behavioral models are co-simulated with flight mechanics and flight control system modules, building on the work presented in**Error! Reference source not found.**.
The results provide an assessment of the ODP impact on the efficiency and consistency of the HER aircraft design process. Finally, possible future developments of the platform are outlined, highlighting the additional capabilities that could further reduce development time and costs.

3. Results / Conclusions

This article highlights the main capabilities of the ODP by describing how it can support the design and integrated Virtual V&V of a HER aircraft throughout the entire development process. The analysis also provides a validation of the ODP across the full design cycle. Finally, possible future developments of the ODP modules are outlined.

Automated Validation and Verification in Aircraft Design: Integrating MBSE and MDO

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1. Introduction / Objectives

This work presents a unified digital-thread approach for aircraft design, integrating requirement definition, system architecture, design, and analysis via an Open Digital Platform (ODP) developed under the ODE4HERA Clean Aviation Project. The framework facilitates integrated validation and verification (V&V) by ensuring design compliance with predefined requirements. To maintain semantic continuity, the approach leverages SysML v2 and a dedicated ontology, while Functional Mock-up Units (FMUs) enable time-domain behavioral simulations. By automating the generation of behavioral models that are consistent with the multidisciplinary modeling approach, the framework enhances traceability, reproducibility, and rapid iteration. Using a distributed hybrid-electric regional aircraft as a case study, this research demonstrates the integration of Model-Based Systems Engineering (MBSE), Multidisciplinary Design Optimization (MDO), and FMU-based co-simulation into a robust, end-to-end V&V workflow. The core innovation lies in the seamless integration of SysML v2, MDO, and behavioural simulation to accelerate clean-aviation technology development.

2. Methodology

The proposed approach is founded upon a SysML v2-based MBSE environment that captures top-level requirements, functional decomposition, and multidisciplinary design data. Requirements are modeled with explicit attributes (subjects, units, reference values, and fulfillment relations) and are mapped to the overarching ontology to guarantee semantic consistency across all downstream artifacts. The system architecture defines the components, interfaces, and reference points that serve as the primary source for optimization design variables. The requirements, the architecture and the multi-disciplinary analysis and optimisation problems are supported by a common ontology and a digital thread leveraging SysML v2 and the Syside . Using the gemseo-SysML v2 connector, the MBSE model is parsed to extract the design variables, constraints, and objective functions, which are then mapped onto the GEMSEO optimisation engine . Consequently, the MDO process, encompassing discipline definitions, convergence methods, and scenario types, is no longer a manually crafted script, but a model-driven artifact residing within the MBSE environment.

An Open Digital Platform (ODP) bridges these MBSE artifacts with Functional Mock-up Units (FMUs) representing flight mechanics , aerodynamics, and on-board systems models. Each FMU is coherent with the modelling used by the MDO framework, leveraging GEMSEO , exposing critical operational inputs (e.g., thrust demand, ambient conditions) and outputs (e.g., lift, drag, electrical power, state-of-charge). These FMUs are orchestrated within a time-domain simulation environment, allowing the aircraft's trajectory, power demand, and system dynamics to evolve synchronously through co-simulation. The requirements, modelled by the MBSE framework, are directly converted in functional tests and the behavioural models are used, based on the prescribed mission, to automatically span all the requirements and return their status. The use case is distributed propulsion HER configuration (see Figure 1). To demonstrate this end-to-end capability, three mission profiles were executed: a nominal gate-to-gate flight, a diversion (climb-hold-descent), and a step-cruise sequence. The simulations confirmed that the aircraft adheres to prescribed trajectories, respects current limits, and maintains the battery state-of-charge within the defined envelope, thereby validating the integrated MBSE-MDO workflow.

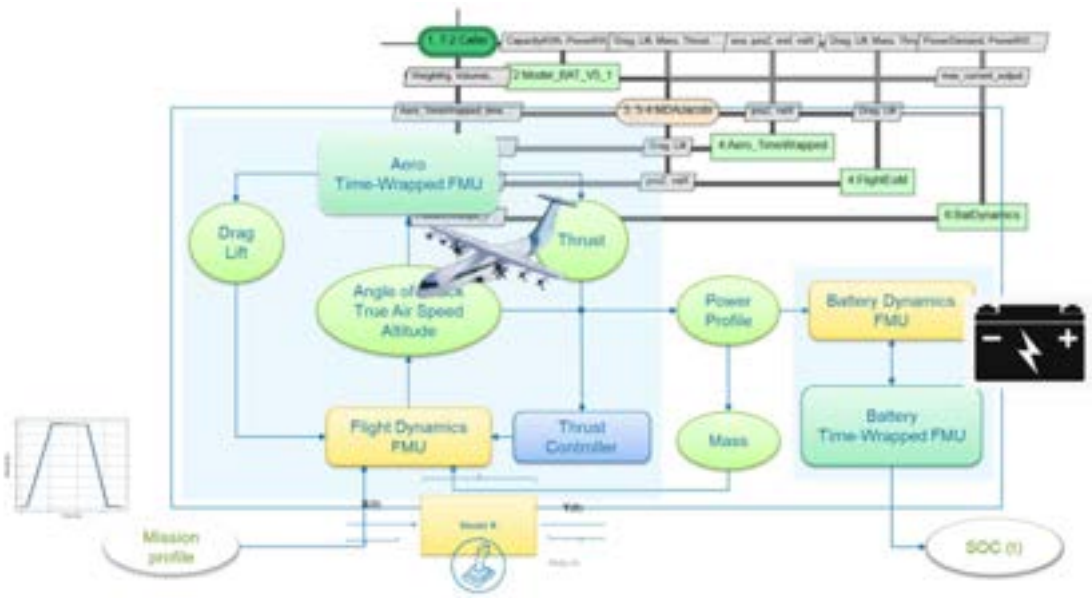


Figure 1. *Sketch of the Behavioural Model Approach.*

3. Results / Conclusions

This work demonstrates that a model-driven digital thread can successfully link MBSE artifacts to an MDO engine and subsequent FMU-based behavioral simulations. The primary novelty lies in the automated generation and updating of the MDO problem directly from the SysML v2 architecture, effectively bridging the traditional gap between systems engineering and multidisciplinary optimization. The successful application to a Distributed Electric Propulsion (DEP) concept establishes a robust foundation for the digital-first development of hybrid-electric aircraft. Furthermore, this framework provides a scalable architecture that can be extended to include additional disciplines, such as thermal management and acoustics, and integrated with broader mission-profile libraries to support complex, next-generation aviation certification and design workflows.

Open Digital Environment integrating Systems into Preliminary Aircraft Mission Simulation and Optimization

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1. Introduction / Objectives

The EU-funded Clean Aviation projects propose novel hybrid-electrical aircraft architectures as a promising solution to reduce emissions. However, current conventional approaches for aircraft design are unable to efficiently capture the increased multidisciplinary and system complexity. One potential solution is model-based requirement verification based on a Multidisciplinary Design Optimization (MDO)-capable numerical mission simulation and optimization framework.

2. Methodology

Existing component models are integrated into an MDO-framework to assemble a model representation of the subject hybrid-electrical aircraft. Based on these, the identified key disciplines contributing to the different requirements are modeled.
Simulation data management is meant to provide traceability amongst models of different domains and track changes within the evolution of a single model. Early virtual verification of requirements can be supported by these technologies (see Figure 1). In the ODE4HERA project an open digital platform (ODP) is proposed to store and exchange data of different simulation tools in a central data storage. The data structure is defined in SysML v2 tool-agnostic libraries . So far, the simulation domain was tested with a system simulation model in Amesim . For aircraft design, detailed simulation and domains like FEM and CFD are highly relevant. In this paper investigations will be made into how to connect these domains and detailed models to the ODP.

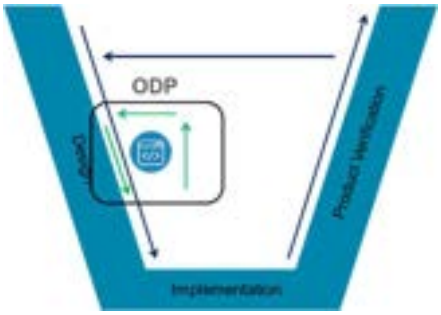


Figure 1. *Model based requirement verification.*

3. Results / Conclusions

An analysis illustrating the model-based requirement verification is conducted to show how to bridge the gap between physical models and model-based system engineering while optimizing specific requirements. direct aeroelastic analysis for mission simulation purposes. Nevertheless, the implementation could pave the way for future coupled structural and mission trajectory optimizations.

Acknowledgement: The research presented in this paper is performed within the framework of the ODE4HERA project (Open Digital Environment for Hybrid-Electric Regional Architectures), which has received funding from the European Union Clean Aviation Joint Undertaking under Grant Agreement No. 101140510. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation.

Evaluation of Flight Systems by Interfacing FMI based Co-Simulations with the Aircraft & System Design through SSP

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1. Introduction / Objectives

Modern and increasingly electrified aircraft system technologies are growing more complex due to the stronger coupling between mechanical, electrical, thermal, and control domains. Simultaneously, it is beneficial to assess new system technologies such as the ones found in electric flight control as early as possible to avoid costly changes further down the development chain. This is challenging when subsystem models are developed separately or evaluated using simplified boundary conditions as there can be highly dynamic cross-coupling effects between subsystems that need to be considered.
Therefore, the objective is to develop a seamless, modular, dynamic simulation process to enable an early evaluation of system technologies at aircraft level. The proposed method aims to connect aircraft design data to dynamic system simulations.

2. Methodology

With the advent of the established Functional Mock-up Interface (FMI) standard and the new System Structure and Parameterization (SSP) standard there is an opportunity to develop comprehensive, cross-domain models at an early design stage and to establish a closer link between system design and dynamic simulation. This paper presents the co-simulation framework developed as part of the DLR SMART project. Figure 1 gives an overview of this framework. The aim is to improve the design assessment capabilities by using dynamic simulation results. This primarily involves dynamic effects, such as mechanical and electrical load peaks, which must be taken into account even beyond system boundaries. To set up and configure the co-simulation, the necessary information is imported from CPACS (Common Parametric Aircraft Configuration Schema) and SysML v2 and transferred to the SSP. As feedback to the design, selected simulation results, such as electrical power consumption and maximum loads, are exported to the relevant file formats. In this work, we examine the co-simulation between the electrical power supply and the electrical flight control system for a flaperon of the DLR-F25 aircraft as a use case. The focus is on investigating the dynamic interactions in form of the electrical power between the two systems. As a test case, we present the highly dynamic gust load alleviation function.

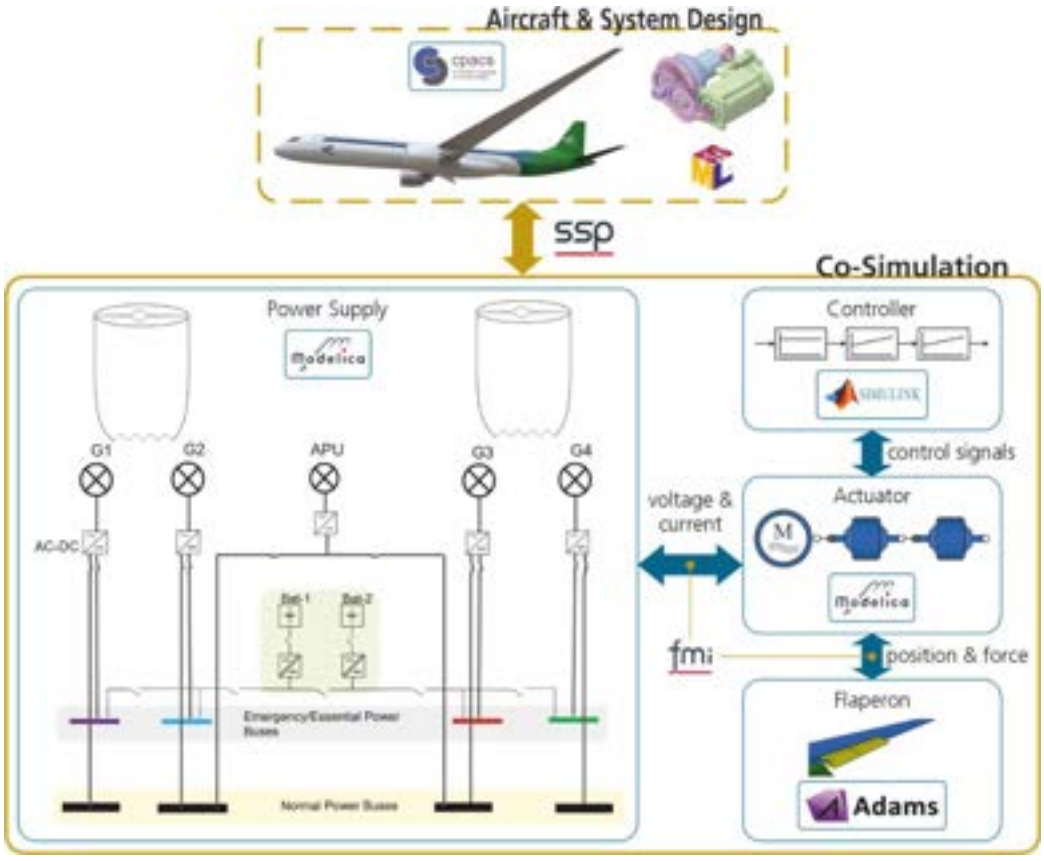


Figure 1. *System architecture and co-simulation framework interfaces*

3. Results / Conclusions

The co-simulation is implemented with a step size that avoids coupling errors while providing timely feedback. The values of several key performance indicators such as battery masses or dynamic actuator drive torques are calculated using the co-simulation and subsequently

provided to the overall aircraft design. It is presented how the related aircraft requirements can then be evaluated using this method. Finally, lessons learned during the implementation of the co-simulation framework are summarized and an outlook for future improvements is given.

Virtual and Connected Testing of Hybrid Electric Networks

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1. Introduction / Objectives

Currently, functional and non-functional testing of hybrid electric aircraft networks in the real world is resource-intense, causing high costs and has limitations for certification, as shown in Figure 1. Transitioning to virtual testing utilizing a strong Model-Based Systems Engineering (MBSE) process linked to Software-in-the-Loop (SiL), Hardware-in-the-Loop (HiL) and Ground Test environments, composed of simulation, emulation and real equipment, offers a more efficient approach.
However, higher abstraction levels necessitate higher credibility assessment efforts in the development process. The effort required for model validation and the necessary resources do not change continuously during the transition from one test environment to another, but rather non-linearly. For example, the transition from Ground Test to Flight Test requires a full system integration with real equipment. Therefore the proposed paper describes a novel approach for a virtual system integration at aircraft level for hybrid electric architectures at a Ground Test facility.

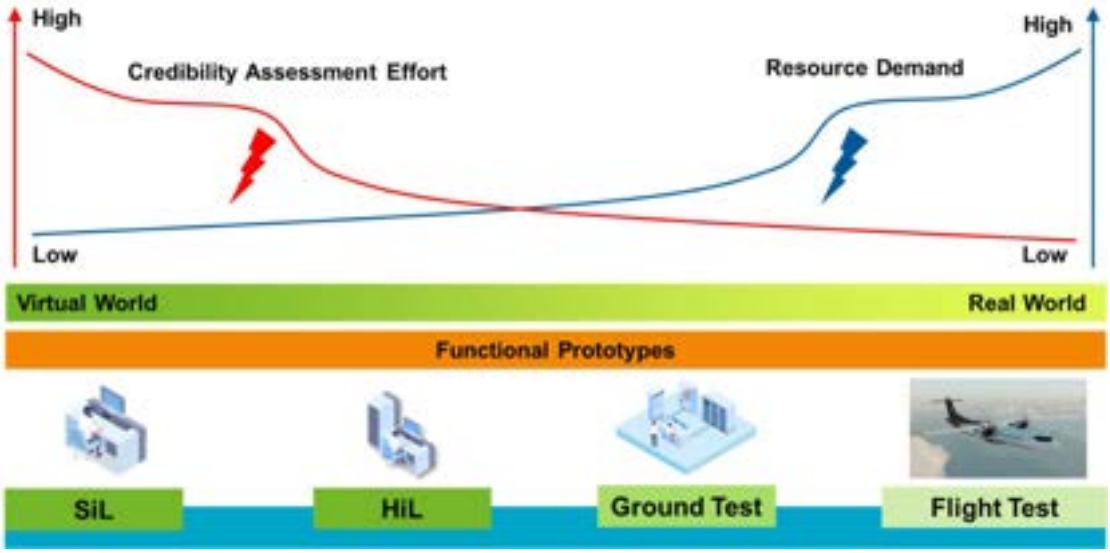


Figure 1. *Virtualization in the development process.*

2. Methodology

In the LEIA project , AVL supports the development of a Ground Test Demonstrator (GTD) by means of virtual and physical integration. This includes the integration of motor-generators, power electronics, converters and batteries either as real equipment or using real-time models on emulators as shown in Figure 2. For the required validation of the High- and Low-Voltage networks, the operational condition of the aircraft and environment is represented by a real-time system model. The GTD has the ability to interconnect to remote sites with component test benches for loads or other equipment. The test environment can be controlled by a novel automated integration and model management software, connected to existing requirement and data analytics tools.

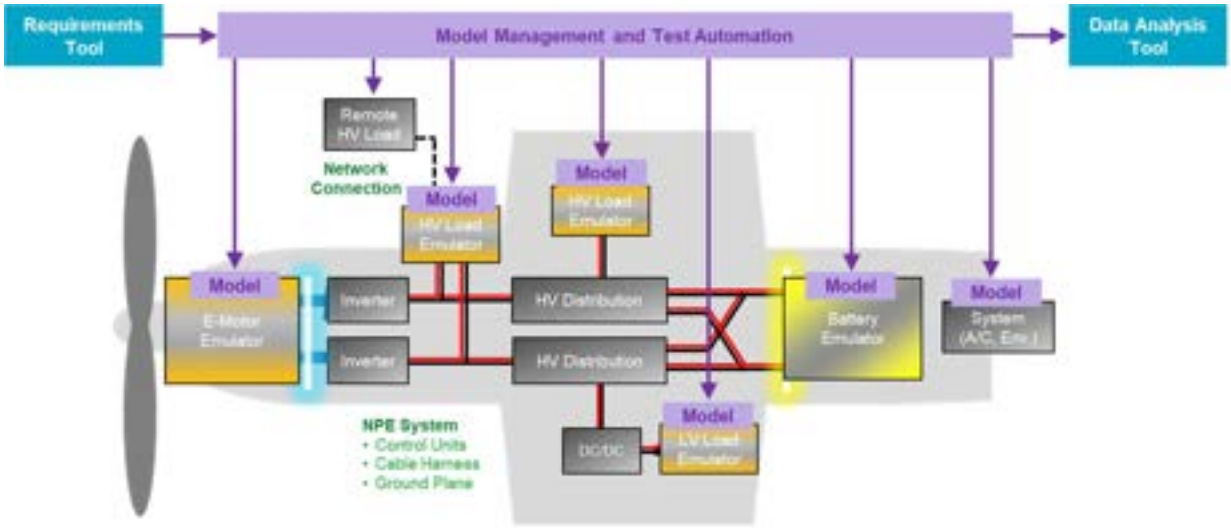


Figure 2. *Example for ground test of a hybrid electric network.*

3. Results / Conclusions

A flexible workflow with models of scalable fidelity utilizing standardized interfaces demonstrates the feasibility to connect real parts with emulated parts on a HV network at the GTD. It also shows to ability to interlink the GTD to test benches on geographically distant locations over a fast digital network.

Acknowledgement: Funded by the European Union under Grant Agreement No 101255065. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

Model-Based Systems Engineering for Early Zonal Hazard Identification in Aircraft System Design

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1. Introduction / Objectives

Early-stage aircraft design decisions strongly influence system safety and integration. Conventional hazard analysis methods are typically applied in later phases, limiting their ability to guide conceptual design. With increasing system complexity, there is a need for approaches that enable early safety assessment. This work proposes a Model-Based Systems Engineering (MBSE)-driven framework for early zonal hazard identification. The approach integrates functional system architecture with spatial configuration, enabling identification of safety-critical interactions during conceptual design. The overall aircraft configuration and fuel system layout considered in this study are illustrated in Figure 1.

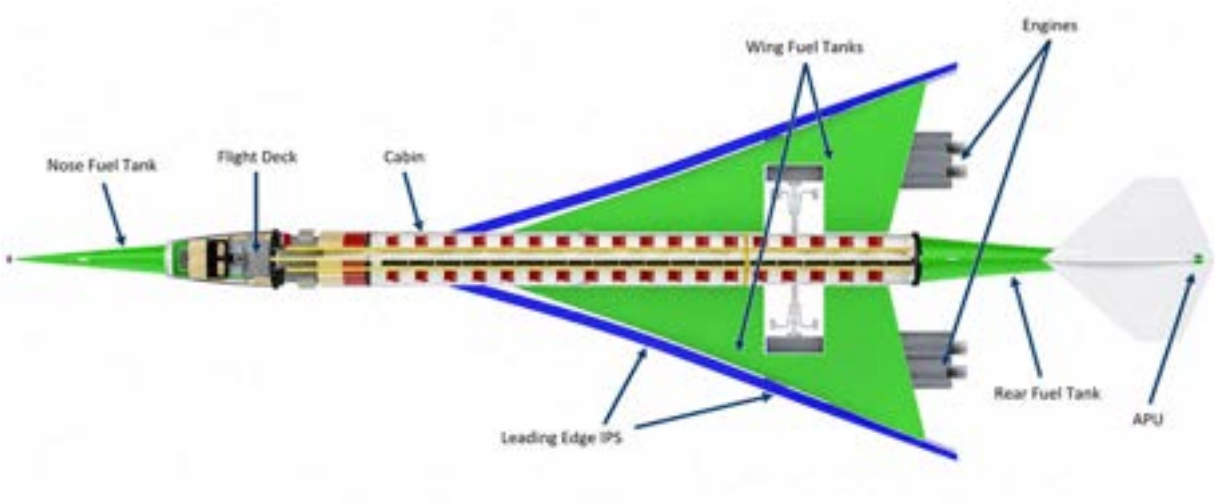


Figure 1. Zonal configuration of the conceptual aircraft fuel system highlighting key subsystems and potential hazard interaction regions.

2. Methodology

The proposed framework integrates MBSE with Computer-Aided Design (CAD) to support early hazard identification. Functional system relationships are defined within an MBSE environment, while CAD models represent subsystem spatial configuration. Zonal analysis is then applied to evaluate interactions based on physical proximity and system behaviour. Hazards such as thermal exposure, leakage, and subsystem interference are identified using structured reasoning approaches including fault-tree-based analysis. The integration enables traceability between system architecture and safety considerations, supporting iterative refinement. The overall workflow linking CAD geometry, MBSE system architecture, and hazard identification is presented in Figure 2, highlighting the feedback loop between design and safety assessment.

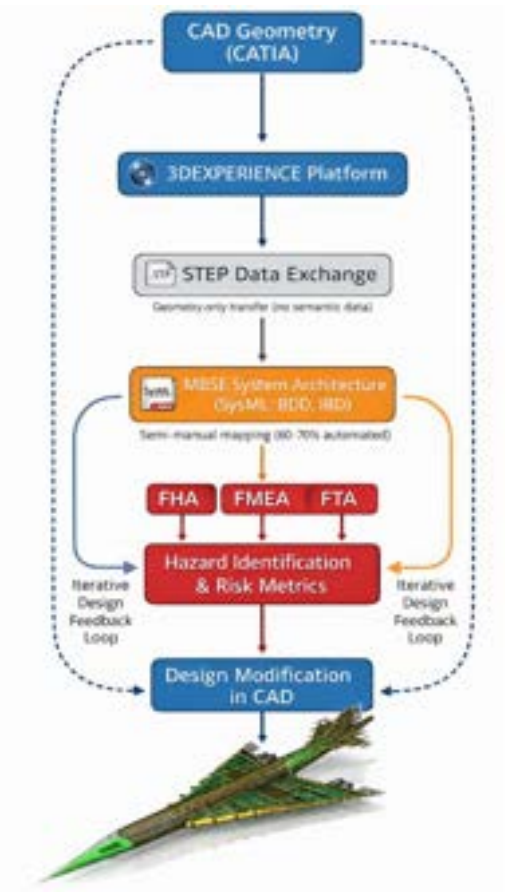


Figure 2. Integrated MBSE–CAD framework for early zonal hazard identification in conceptual aircraft design.

3. Results / Conclusions

Application of the framework to a conceptual supersonic aircraft fuel system demonstrates improved early identification of hazard-prone configurations. Key risks, including thermal interactions and system interference, were identified at the conceptual stage, reducing reliance on late-stage analysis. The results show that integrating MBSE with spatial design enhances traceability and supports proactive safety-driven design decisions. The proposed approach contributes to digital engineering practices for safer and more efficient aircraft systems.

Extending SysML v2-Based MBSE–MDAO Integration to Uncertainty and Multi-Fidelity Optimisation: Application with GEMSEO to a Hybrid-Electric Regional Aircraft

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1. Introduction / Objectives

Bridging Model-Based Systems Engineering (MBSE) and Multidisciplinary Design Analysis and Optimisation (MDAO) is essential for aerospace digital threads, yet industrial workflows remain fragmented across requirements, architecture and optimisation environments. Earlier work introduced a SysML v2 Problem–Strategy–Solution metamodel and a prototype connector to GEMSEO , demonstrating deterministic digital continuity and closed-loop requirement verification on a simplified Thermal Management System.

Industrial hybrid-electric aircraft design, however, requires capabilities beyond deterministic, scalar and single-fidelity optimisation. The involved disciplines may be affected by uncertain variables and parameters, driven by variable operating conditions or incomplete early-design knowledge. This paper extends the SysML v2 MBSE–MDAO metamodel with uncertainty, probability and sampling constructs, tensor-structured variables and multi-fidelity workflow representation. Implemented in the open-source gemseo-sysmlv2 package, the approach targets the second use case (UC2) of the ODE4HERA project, based on the HERA aircraft.

2. Methodology

The proposed methodology extends the SysML v2 Problem–Strategy–Solution metamodel introduced in from deterministic MDAO toward uncertainty-aware and multi-fidelity optimisation. The original structure is preserved: the Problem captures the design space, objectives and constraints; the Strategy captures the MDAO formulation, disciplines, optimizer and convergence settings; and the Solution records optimisation outcomes and requirement-verification evidence. Compared with the deterministic workflow, the SysML v2 exchange model is enriched with three complementary libraries: Probability and Sampling, Tensor/Vector/Matrix, and a multi-fidelity extension, all connected to GEMSEO through the gemseo-sysmlv2 GEMSEO plugin.

Uncertainty is represented through uncertain variables associated with explicit probability distributions. Uncertainty propagation is specified at the strategy level through sampling and statistical-estimation constructs, such as Monte Carlo sampling. This enables robust or probabilistic MDAO formulations, statistical objectives and uncertainty-aware constraints, such as probabilistic or margin-based, to be described directly in SysML v2.

Tensor-structured variables address the scalar-oriented limitation of the initial metamodel. A tensor descriptor defines the shape, layout, dimension labels and semantics of grouped variables, allowing design variables, parameters and coupling quantities to be organised as vectors or matrices while preserving the engineering meaning of each element and its mapping to numerical arrays.

The metamodel is also prepared for multi-fidelity MDAO, which is under implementation and

will be demonstrated in the final paper. Each discipline may reference several executable model representations, including analytical models, Model-Based Design components, surrogate models or nested MDAO sub-processes, so that fidelity choices remain explicit at the SysML v2 level.
The open-source gemseo-sysmlv2 package implements the approach. A SysMLv2Reader API on top of SysIDE parses the SysML v2 model into a typed Pydantic intermediate representation of the architectural parts and instantiates the GEMSEO scenario. A SysMLv2Writer writes solution values, statistical indicators and requirement-verification status back into SysML v2. The methodology is evaluated on the ODE4HERA UC2, with requirements from ARMADE, architecture from ADORE , and workflows from MDAx or textual SysML v2.

3. Results / Conclusions

The proposed extensions introduce SysML v2 libraries for probability and sampling, tensor/vector/matrix data structures, and multi-fidelity model representation, while preserving the Problem–Strategy–Solution structure and requirement traceability.
The implementation is supported by the open-source gemseo-sysmlv2 package, which parses SysML v2 models, builds a Pydantic intermediate representation of the architectural parts, generates GEMSEO scenarios, and writes solution values, statistical indicators and requirement verification status back into SysML v2 models.
The approach is being applied to the ODE4HERA hybrid-electric regional aircraft second use case (UC2), demonstrating a digital thread of the ARMADE, ADORE, MDAx and GEMSEO tools through SysML v2. The final paper will report the completed multi-fidelity implementation, uncertainty-aware analyses, tensor-structured variable handling and lessons learned on closed-loop requirement verification.

A Modular Digital Engineering Framework for Multidisciplinary Sizing and Integration of Hydrogen-Electric Aircraft Propulsion Systems

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Universidad Carlos III de Madrid, Spain

1. Introduction / Objectives

Hydrogen-electric propulsion systems are considered a promising solution for reducing aviation environmental impact, particularly for general aviation and regional aircraft . However, the integration of fuel-cell-based propulsion architectures introduces strong couplings between propulsion, thermal management, aerodynamics, and auxiliary systems, which are not adequately captured by conventional sequential conceptual-design methodologies.
This work presents a modular physics-based Multidisciplinary Design Analysis and Optimisation (MDAO) framework for the integrated sizing and assessment of hydrogen-electric propulsion systems within a digital engineering environment. The proposed methodology enables coupled multidisciplinary analyses while maintaining subsystem modularity and extensibility. The innovation of this work lies in the development of an incremental optimisation architecture capable of consistently integrating propulsion, thermal, aerodynamic, and Balance of Plant (BoP) interactions using physics-based subsystem models.

2. Methodology

The framework is implemented using OpenMDAO , enabling multidisciplinary coupling and gradient-based optimisation. An incremental development strategy is followed, where subsystem models are first validated independently before integration into a coupled optimisation environment.

The framework combines models for the Proton Exchange Membrane Fuel Cell (PEMFC), Balance of Plant, thermal management system, air intake, electric motor, and propeller. The PEMFC model is based on electrochemical polarisation relations combined with species balance and thermal equilibrium equations . Auxiliary systems, including air compression and humidification, are explicitly included to account for their impact on efficiency, thermal loads, and power demand. Additional power is supplied by a Li-Ion battery to account for unsteady requirements.

Thermal management is addressed using compact heat-exchanger formulations under steady-state conditions . The cooling-air intake is modelled using a one-dimensional compressible-flow formulation including isentropic, Rayleigh, and Fanno flow effects . Heat exchanger integration introduces pressure losses and flow blockage, enabling the evaluation of cooling-drag trade-offs within the propulsion-system optimisation process .

The electric propulsion chain includes a Permanent Magnet Synchronous Motor (PMSM) coupled with a Blade Element Momentum Theory (BEMT) propeller model incorporating compressibility and finite-blade corrections . Figure 1 shows the architecture multidisciplinary interactions between the components.

3. Results / Conclusions

The proposed framework establishes a modular digital engineering environment for the preliminary design of hydrogen-electric aircraft propulsion systems. The methodology enables the consistent coupling of propulsion, thermal management, aerodynamic, and auxiliary subsystem models within a unified optimisation workflow.

Preliminary analyses at different flight conditions demonstrate the capability of the framework to optimize the system capturing the coupled interactions between all subsystems, allowing multidisciplinary trade-off analyses typically neglected in conventional conceptual-design approaches.

The framework provides a scalable foundation for future sustainable aviation architectures optimisation, mission analysis, and integration with broader environments.

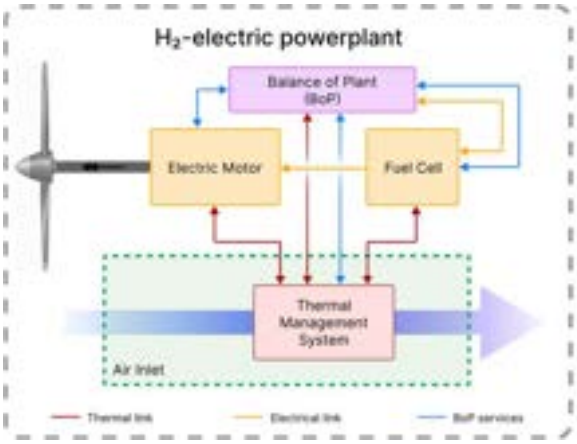


Figure 1. *Schematic representation of the MDAO framework and couplings between propulsion, thermal management, aerodynamics, and BoP subsystems.*

Exploration of Machine Learning-Assisted Multidisciplinary Design Optimization Methods in Aircraft Conceptual Design Using Digital Twin Technology

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1. Introduction / Objectives

The aviation industry has increasingly adopted digital transformation due to the growing complexity of modern aircraft systems, driven by advanced avionics, health monitoring technologies, and integrated sensor networks . In this context, Digital Twin (DT) technology has emerged as a strategic solution, enabling continuous interaction between physical assets and their virtual counterparts through real-time data exchange , . However, conventional DT frameworks relying on physics-based models often face computational limitations in multidisciplinary aircraft design applications.
The integration of Machine Learning (ML) has enhanced DT capabilities by enabling adaptive surrogate models that significantly reduce simulation time while maintaining predictive accuracy , . Motivated by these advancements, this study aims to develop a machine learning-assisted digital twin framework for aircraft conceptual design optimization. The proposed approach introduces an intelligent, data-driven methodology for efficient multidisciplinary design optimization, contributing to next-generation aerospace design practices.

2. Methodology

A machine learning-assisted digital twin framework was developed for multidisciplinary design optimization (MDO) in aircraft conceptual design. First, a parametric design environment was established to define key aircraft design variables, including aerodynamic, structural, propulsion, and mission-related parameters.
High-fidelity multidisciplinary simulations were then performed to generate a comprehensive training dataset. Based on this dataset, supervised machine learning models were trained to predict system responses and construct surrogate models for the digital twin. These models were integrated into the optimization framework to enable rapid evaluation of design alternatives with reduced computational cost. The developed digital twin was employed to perform iterative design optimization under predefined objectives and constraints, such as minimizing weight and maximizing aerodynamic efficiency. Finally, the predictive performance of the digital twin was validated against selected high-fidelity simulation results to assess accuracy and computational efficiency.

3. Results / Conclusions

The proposed machine learning-assisted digital twin significantly reduced computational time while maintaining acceptable prediction accuracy in multidisciplinary aircraft design analyses. The framework enabled rapid exploration of the design space and effective identification of optimal design solutions.
The results demonstrated that integrating machine learning with digital twin technology can improve efficiency and support faster, data-driven decision-making in aircraft conceptual design.

Sequential Sampling Algorithm for the Design of a Hybrid-Electric Regional Aircraft under Uncertainty

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1. Introduction / Objectives

This paper presents a sequential multi-fidelity strategy for robust optimization under uncertainty in multidisciplinary aircraft design (UMDO). The proposed approach uses adaptive fidelity levels by progressively increasing the number of samples used for statistics estimation and decreasing the tolerance on optimization convergence (stopping criterion). The method begins from an initial starting point, and then each level of fidelity is warm-started from the optimal solution found at the previous one. In this paper, a rule is proposed to define the allocation of number of samples and tolerances across fidelity levels, to reduce the computational cost of solving the UMDO problem while ensuring the solution accuracy. An alternative approach proposed automates the switch from one level to another using a statistical test, thereby avoiding the need to specify tolerances (which are useful for deterministic quantities) on stochastic quantities (e.g., the expected value of the objective function).

2. Methodology

We propose a sequential multi-fidelity approach based on iterative refinement . Each fidelity level is characterized by a tolerance (used to stop the optimization process) and a number of samples (used to estimate the statistics), the former decreasing and the latter increasing with the fidelity level. The disciplines remain the same across levels. Starting from an initial guess, the UMDO problem is solved sequentially from the lowest to the highest fidelity level: the solution obtained at a level serves as a warm start for the next level, and the switch is triggered when the optimization tolerance at the current level is reached.
Initial experiments have shown that intermediate fidelity levels should not consume too much budget , and that three levels is a good choice. The number of samples and tolerance for the lowest and highest levels are given. In the context of three levels of fidelity, the number of samples (resp. the tolerance) for the intermediate level has to be defined. To obtain a progressive distribution of samples (resp. tolerances) that is more concentrated towards the lower fidelity settings, a ramp defined by an exponential trend is chosen. With this methodology, the UMDO problem is solved by controlling the computational budget, thanks to one low-fidelity level (to begin the exploration phase), one medium/low-fidelity level (to start converging without consuming too much budget), and one high-fidelity level (to reach the solution with the high-fidelity precision).
Figure 1 presents the evolution of the number samples and tolerance for a simplified Overall Aircraft Design (OAD) in-house case, where the high-fidelity level is defined by 160 samples and a tolerance of 10^{-8}.

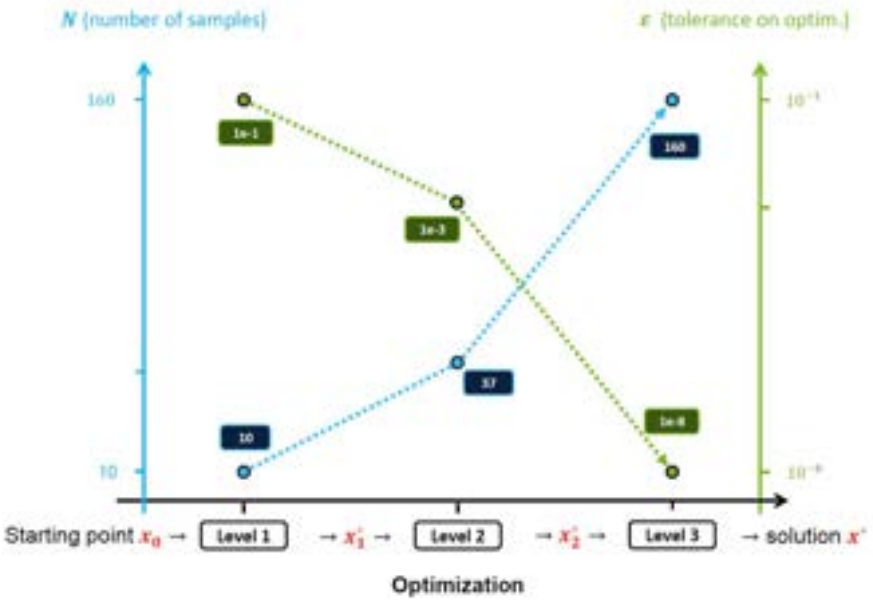


Figure 1. *Evolution of the number of samples and tolerance based on an exponential trend, for three levels of fidelity.*

A second approach proposed in the paper replaces the specified tolerances, which are relevant for deterministic quantities, by statistical tests more suited for stochastic quantities. This more advanced criterion uses the p-values concept to detect convergence of the solution and automatically switch to the next level of fidelity.
The proposed approach was implemented using the Python library *gemseo* and the *gemseo-umdo* plugin for solving UMDO problems.

3. Results / Conclusions

The methodology has been first tested and validated on a simplified OAD problem. This validation phase allowed to confirm that three levels of fidelity defined according to the exponential rule proposed for selecting sample sizes and tolerances is an appropriate choice for controlling calculation costs while keeping solution accuracy. Furthermore, the second approach which employs a statistical test as stopping criterion (better suited to UMDO problems) to replace tolerances on optimization, also helped to improve the proposed method. Finally, the proposed approach has been applied to a hybrid-electric regional aircraft problem, demonstrating the scalability of the approach on a realistic design case.

Towards a Scalable Reference Architecture: Matrix-based Approach to Scalable High-Level Requirements for Next-Generation Military Integrated Modular Avionics (NG-MIMA)

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1. Introduction / Objectives

Integrated Modular Avionics is a shared set of interoperable hardware and software resources forming a platform that hosts applications performing aircraft functions . The NG-MIMA project seeks to define a **N**ext-**G**eneration **M**ilitary **IMA** platform supporting a wide spectrum of military aircraft. Current IMA architectures are usually aircraft-specific and therefore lack a systematic method to adapt requirements to the diverse space, weight, power and operational constraints of different classes of aerial platforms. In the consortium of 21 European partners, Airbus Defence and Space GmbH leads this study introducing a novel scalability framework that couples requirements with a set of performance metrics that act simultaneously as design drivers and performance indicators. The metrics are mapped onto four generic prototypical platforms, each representing a relevant military aircraft class. The objective is to generate requirements that are adaptable to these prototypical platforms, providing the foundation for the development of a scalable NG-MIMA reference architecture.

2. Methodology

The work was organised in an approach consisting of four major steps, separating requirement definition from metric quantification and then merging the independent strands trough a scalability matrix:

1. **Elicitation of High-level Requirements (HLRs)**
   Applying the requirements definition process defined in , a set of HLRs was captured based on formalised user needs and operational use cases. Validation of the HLR set in scope of was performed through continuous interaction with the consortium partners and domain experts. Each requirement was recorded with a unique identifier, rationale, and traceability attributes.
2. **Compilation of a portfolio of performance metrics**
   A portfolio of performance metrics similar to the Measures of Performance defined in was complied, focusing on computational, communication, and interface capabilities. This step was performed independently of the HLR elicitation to avoid bias. The performance metrics were then linked to applicable HLRs, replacing hard-coded values inside their definition with references. This yielded parametric requirements and exposed potential gaps in either the HLR set or the metrics portfolio.
3. **Definition of the prototypical platforms**
   Four generic aircraft classes were defined in this third independent step, representing major military aerial platform categories. For each class, characteristic constraints like space, weight, power, or deployment scenario were quantified. The prototypical platforms serve as scaling factors for the HLR set by applying platform-specific limits and characteristics to the performance metrics' values.

4. **Construction of a Scalability Matrix**
   The described independent strands were merged into a scalability matrix by assigning numerical values to each metric-platform pair, creating a scalable mapping. This allows requirements to be instantiated with different numerical values depending on the platform class, which is an integral characteristic of scalable reference architectures. The matrix also supports traceability, enabling impact analysis and comparative evaluation across IMA platforms.

The methodology deliberately separates metric definition from requirement elicitation, then re-integrates them with the prototypical platforms through the scalability matrix. This approach ensures that HLRs remain adaptable without redefining the underlying performance targets for each platform. Vice versa, it enables the scalability mechanism to be reusable for future platform classes or updated metric sets without redefining the HLRs.

3. Results / Conclusions

The process delivered a coherent baseline of HLRs together with a portfolio of performance metrics and a set of four prototypical platform models. By applying the scalability matrix, metric values are automatically adapted to each platform class, providing a single, scalable specification that can be reused across a wide spectrum of military aircraft. This enables early trade-off studies, consistent qualification, and straightforward comparison with alternative avionics solutions. The methodology demonstrates that scalability of high-level requirements can be achieved without proliferating separate requirement sets, paving the way for a flexible and scalable reference architecture for NG-MIMA and offering a template for other modular avionics programmes.

Natural Language Processing for Pilot Intent Recognition in Next-Generation Fighter Cockpits: a Proof-of-Concept and its Assessment Approach

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1. Introduction / Objectives

The EPIIC ("Enhanced Pilot Interfaces & Interactions for Fighter Cockpit") project addresses a defining challenge for next-generation air combat: enabling a single pilot to serve as the mission-level supervisor for crewed and uncrewed platforms operating in dense, time-critical, data-intensive environments. Sustaining this supervisory role demands interaction paradigms that minimize cognitive load while maximizing situational awareness and decision speed. Natural Language Processing (NLP), driven by recent advances in conversational AI and multimodal interaction , is emerging as a key enabler in this domain: spoken interaction offers a hands-free channel that, in principle, requires no pilot-specific training. This work introduces a proof-of-concept NLP architecture for pilot intent recognition and a structured methodology to assess its operational value, aiming to consolidate technology requirements and guide the maturation of voice-based cockpit interaction toward future combat systems.

2. Methodology

The proposed architecture, shown in Figure 1, organizes the recognition pipeline into four cooperating modules. Voice Detection captures the pilot's voice command and converts it

into a normalized audio stream. Automatic Speech Recognition (ASR) transcribes the audio into text and is built on the OpenAI Whisper pretrained model, leveraging the robustness to noisy speech that is now standard in modern speech processing . Text-to-Intent (TTI) classifies the transcribed command into one of a curated set of pilot intents, while Named Entity Recognition (NER) runs in parallel, extracting the operational entities (systems, targets, parameters) referenced in the command.

A distinguishing design choice is the hybrid resolution of TTI and NER, which couples a traditional deterministic rule-based engine with a more modern solution based on Large Language Models (LLMs) . The rule-based layer handles canonical phrasings with very low latency and predictable and auditable behavior; properties essential in a safety-critical cockpit context. When the rule-based layer fails to produce a confident match, the LLM is activated as a fallback, restoring coverage for paraphrased or unusual formulations while preserving the required responsiveness (less than 1 second). Once intent and entities are resolved, they are merged into a single structured command directed to the Fighter avionic system.

Training and evaluation rely on a corpus of intent-labeled sentences generated offline. The generator combines avionic commands with the entities relevant to each operational scenario, expanding each command into the full space of plausible pronunciations and lexical variants. Sentence generation is grounded in real pilot phraseology, so the model is exposed to commands that match actual cockpit usage.

The assessment framework rests on three primary parameters: accuracy, the share of correctly recognized intents on a held-out evaluation set; latency, measured from the end of the spoken command to the issuance of the recognized intent; and speed of interaction, the time required by the pilot to issue a complete command. Time-tagged performance traces support comparison against literature baselines and an analysis of overall interaction effectiveness.

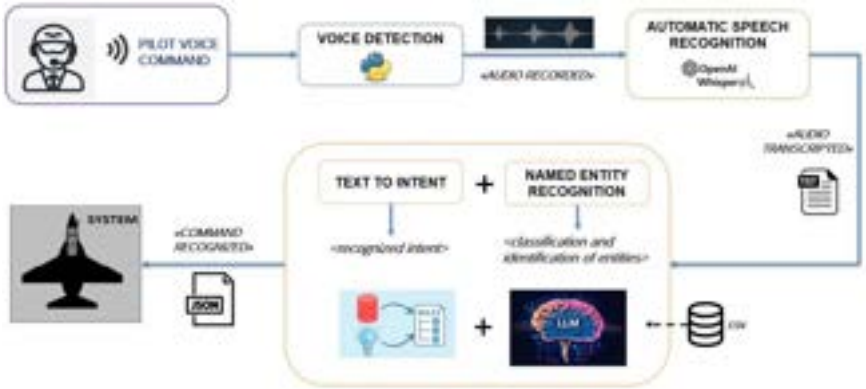


Figure 1. *End-to-end NLP architecture for pilot intent recognition: voice detection, Whisper-based ASR, and parallel Text-to-Intent and Named Entity Recognition modules combining a rule-based engine with an LLM fallback.*

3. Results / Conclusions

Preliminary evaluation of the proof of concept confirms the value of the hybrid recognition strategy. With only the rule-based engine active in the TTI and NER modules, end-to-end intent recognition success rate (percentage of time the command is correctly interpretated) remained below 55%, reflecting the limited coverage of fixed rules against the lexical variability of real pilot speech. Re-running the same evaluation with the LLM enabled as a fallback raised the success rate up to 89%, with no perceivable latency penalty for the

operator. This confirms that a rule-first / LLM-fallback decomposition can reconcile the deterministic, low-latency behavior required in the cockpit with the linguistic robustness of modern conversational AI. The outcomes will be used to consolidate technology requirements for the EPIIC pilot–system interaction stack and to define the next stages of maturation, including richer multimodal fusion, integration with mission-level supervisory tasks, and operational validation with pilot subjects.

Intelligent Digital Twinning of UAVs Using Residual Learning with Reservoir Computing

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1. Introduction

Physics-based UAV digital twins built from motor, battery, controller, and six-degree-of-freedom rigid-body modules provide interpretable simulation baselines. However, the module open-loop rollout can diverge when driven by real actuator logs because of thrust-mapping errors, battery effects, state-estimation noise, and initial-condition mismatch. Pure data-driven models can reduce short-term errors but may obscure the physical relationships required for a credible digital twin. This study proposes a physics-structured hybrid modelling framework for a Crazyflie UAV digital twin . The objective is to retain a nominal Simulink quadrotor model as the physical backbone while using reservoir computing only as a residual corrector, improving long-horizon prediction without replacing the physics structure.

2. Methodology

The proposed method combines a nominal Simulink quadrotor model with reservoir computing (RC) residual learning. RC is a recurrent time-series learning framework in which the system history is projected into a nonlinear feature space , while only the final readout layer is trained. This makes it suitable for short flight-log datasets, because the model can capture local temporal dependencies without requiring a large deep neural network. In this work, RC is used as a residual corrector rather than as a standalone black-box predictor.
The physical backbone is a Simulink Crazyflie digital-twin model composed of motor, battery, thrust and torque mixing, and six-degree-of-freedom rigid-body dynamics. Given the current UAV state, motor commands, and battery voltage, the Simulink model produces a one-step physical prediction. During training, this one-step prediction is compared with the measured next state, and the difference is used to define the residual-learning target. The RC input includes delayed state variables, motor commands, battery voltage, and nonlinear mixing-related terms, so that the learned correction depends on both recent motion history and actuator excitation.
The residual target is deliberately restricted to translational velocity, Euler attitude, and body angular rate. Position is not directly corrected by RC. Instead, after the velocity residual has been estimated, damped, and clipped, the position is updated by integrating the corrected velocity. This design is important because direct position correction could make the model appear accurate while hiding accumulated velocity bias. During test rollout, the hybrid model propagates from its own predicted state: Simulink first generates the next physical prediction, RC estimates the local residual correction, and the corrected state is then used for the next step, as shown in Figure1. The method is evaluated against a pure Simulink open-loop rollout from the same initial condition.

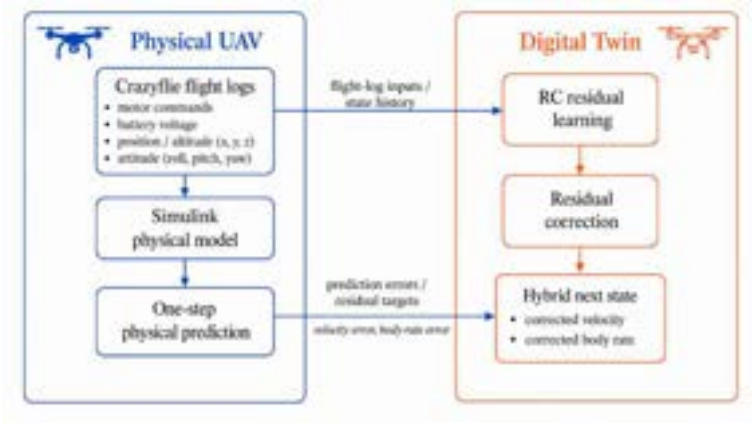


Figure 1. *Simulink–RC hybrid digital-twin workflow.*

3. Results / Conclusions

Preliminary results show that the proposed hybrid model reduces the open-loop drift observed in the pure Simulink rollout, especially in the translational motion, where accumulated physics-model error is visibly suppressed after residual correction. The attitude response is not substantially improved, which suggests that the current RC correction mainly compensates for translational drift rather than fully modelling attitude or yaw transients. This is still a useful result for digital-twin modelling: the data-driven component improves rollout behaviour while the motor--battery--rigid-body structure of the physical model remains explicit. Further work will focus on thrust-parameter recalibration, yaw-related feature construction, and validation across additional flight segments.

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Hybrid-Electric Regional Aircraft behavioral system-level digital twin development

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1. Introduction / Objectives

Commercial aerospace domain and industry are exploring multiple solutions to reduce consumption and pollution to create a cleaner and more sustainable future. The options explored in clean aviation HERA (Hybrid Electrical Regional Architecture) project **Error! Reference source not found.** are based on a mix between hybridization of propulsion system by adding electrical energy (battery or fuel cell) to chemical (kerosene) and several

improvements on the aircraft itself (wings, materials, weight,…). HERA objectives are to design a regional aircraft operationally available in the next coming decades (2035 to 2050), and so is focused on the design of 2 main solutions. This article is proposing to support HER aircraft design: such innovative designs require improvements to Modeling and Simulation (M&S) and the digital twin building **Error! Reference source not found.**. A combined approach joining Mode-Based Systems Engineering (MBSE) **Error! Reference source not found.** and Behavioral system level M&S to support creation and usage of a digital twin, closer to current design stages and needs.

2. Methodology

A digital twin can be created at all stages of design, and for one or multiple purposes. The approach proposed in the article is to create a System-level behavioral digital twin, focused on propulsion system but capturing multiple systems and operationally executable via a simulation which is representing an aircraft mission. By capturing multiple metrics on different systems, like electrical consumption, the aircraft evolution during the mission will support the design, by validating some elected systems requirements or by supporting trade-off analysis.

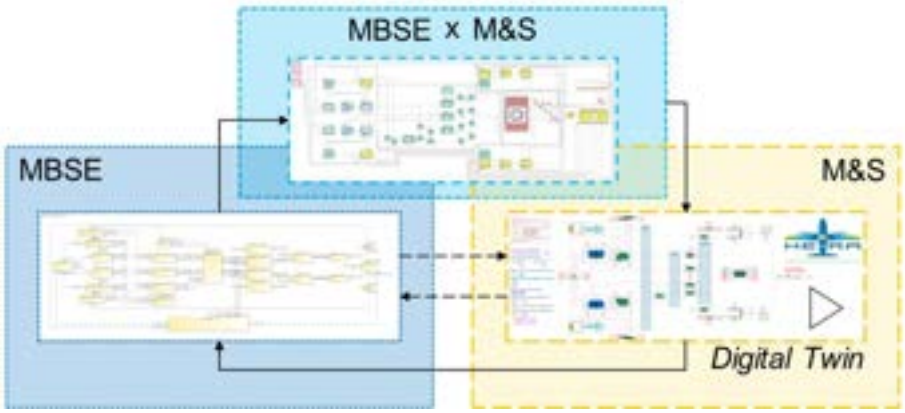


Figure 23 : *Link MBSE to M&S with Architecture-based approach*

The Figure 23 is illustrating the process proposed which is based on the current design gap between system level description and its usage in system level digital twin (arrows in dotted line between MBSE and M&S). The objective is to replace the gap by a direct model-to-model synergy (MBSE x M&S). To support the connection, the Architecture-based approach, composed of blocks and connections is proposed. The benefits expected are:

- Reduced communication errors and improved response time
- Reduced iterations loops and improved model relevancy versus design
- Ensured source of truth information and direct connection to design information
- Improved digital twin building, flexibility, quality and evolution

In order to illustrate and demonstrate the proposed approach, an example around HER aircraft architecture is proposed and analyzed. An example of Digital twin evolution and collaborative development is proposed too. The demonstrator evaluates mission-level indicators such as battery state of charge, electrical power demand, fuel consumption, propulsion power split and requirement compliance over a representative regional mission profile.

3. Results / Conclusions

This article summarized the current status of the work around the digital twin creation to support innovation in aerospace. The process proposed aims to propose a more fluent and model-based interaction between 2 complementary domains and highlight their synergies. The conclusion will highlight the next steps in this workflow and the possible improvements to extend the accuracy of more Digital twin and their creation.

Acknowledgement: The research presented in this paper has been performed in the framework of the HERA project (Hybrid Electric Regional Aircraft) and has received funding from the European Union Clean Aviation Program under grant agreement n°101102007.

A Real-time Digital Twinning Platform for Distributed Electric Propulsion Aircraft Design

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1. Introduction / Objectives

Distributed electric propulsion (DEP) is one of the key technologies for future electric aircraft, bringing new opportunities for aircraft configuration design, high-lift enhancement, and reduced runway requirements . However, DEP aircraft involve strong dynamic coupling among motor response, propeller slipstream, flap–slipstream interaction, wing aerodynamics, flight dynamics, and flight-control behaviour . Conventional isolated subsystem analysis is therefore insufficient for system-level evaluation of DEP aircraft.

This work aims to develop a unified real-time digital twinning platform for the design and assessment of DEP aircraft. In the proposed workflow, the Computational Fluid Dynamics (CFD) is used to verify local propeller–wing–flap aerodynamic layouts, while the X-Plane/MATLAB-Simulink platform evaluates the integrated aircraft-level response under closed-loop flight conditions. This structure enables early-stage subsystem assembly and integrated evaluation of aerodynamic layout, propulsion response, flight dynamics, and control behaviour, supporting future electric aircraft design, digital twin development, and hardware-in-the-loop extensions.

2. Methodology

The proposed methodology uses the platform to connect local aerodynamic verification with aircraft-level system integration. Several propeller–wing–flap layout configurations are first evaluated using CFD to verify the aerodynamic effects of distributed propulsion, including propeller slipstream, flap–slipstream interaction, and wing lift enhancement. The verified configurations are then applied to a modified DEP aircraft model within X-Plane. The modified aircraft is coupled with a Simulink-based electric motor model through a real-time bidirectional interface. X-Plane retains the native gearbox, propeller, aerodynamic forces, aircraft motion, and control-surface effects, while Simulink calculates the motor torque response from flight and propulsion-related states. The motor torque is then fed back into X-Plane and applied via the native propulsion model, with the platform configuration shown in Figure 1.

This workflow enables the platform to evaluate whether CFD-verified aerodynamic layouts remain effective after integration with propulsion dynamics, flight dynamics, and flight-

control behavior. Therefore, the platform supports both aerodynamic concept validation and full-system DEP aircraft design assessment under representative flight conditions.

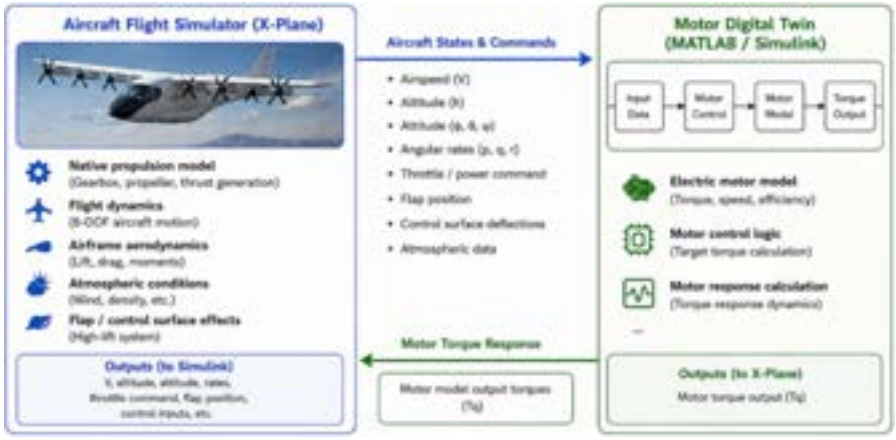


Figure 1. *The Digital Twin Platform configuration.*

3. Results / Conclusions

The CFD-verified propeller–wing–flap configurations were integrated into the X-Plane/MATLAB-Simulink closed-loop platform and assessed under representative flight conditions. Compared with the baseline configuration, the improved DEP configuration reduced lift-off time by 43.3%, lift-off distance by 65.9%, and lift-off speed by 31.8%, demonstrating improved short-field take-off capability. The simulations also revealed a nose-down pitching tendency caused by increased lift and associated aerodynamic moments during take-off, and enabled evaluation of the effectiveness of flight-control intervention. In addition, single-motor and random propulsion-unit failure cases were simulated to assess fault-induced changes in aircraft performance and control behavior. These results demonstrate that the proposed platform can bridge local aerodynamic design and aircraft-level system evaluation, supporting aerodynamic concept validation, full-system integration assessment, and DEP design iteration.

This research is supported by the NEWBORN project, funded by the Clean Aviation Joint Undertaking and its members under the European Union Grant Agreement No. 101101967. UK participants in NEWBORN are supported by UKRI under Grant No. 8219585.

Digital-twin model for assessing energy consumption and efficiency in flight control actuators for new hybrid-propulsion regional aircraft

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HERA is a Clean Aviation project coordinated by Leonardo and aimed at identifying the concept, the possible architectures, and the integrated technologies of a regional aircraft with a hybrid propulsion system in support of sustainability goals. HERA also supports the development of a digital twin for describing, analyzing, and validating aircraft architecture and technologies. In this context, the More Electric Aircraft (MEA) approach applied to flight control systems is well aligned with the ambitions of this project . Electrical actuation systems, employing actuators such as EHA (Electro-Hydrostatic Actuator) and EMA (Electromechanical Actuator), offer several advantages, including increased safety and reliability, reduced weight, easier maintenance, higher energy efficiency, and better dynamic characteristics , . The idea is to progressively replace the hydraulic components with electric devices in order to achieve these benefits. Within this framework, it becomes particularly relevant to carry out a comprehensive energy analysis of such actuation solutions.

As a contribution to the HERA project, this paper presents the development of simplified simulation models for assessing actuator efficiency and ultimately integrating them into a broader aircraft digital twin.

The approach starts from existing high-fidelity models for both actuators, namely an EHA and an EMA, to analyze the energy consumption and efficiency of the main components of the flight control systems. The chosen EHA refers to a primary flight control system, while the EMA refers to a secondary one. For both actuators, the motor's electrical efficiency has been evaluated by using the dynamic signals of the main physical quantities involved in the calculation. In addition, two more elements were investigated in terms of efficiency: the pump for EHA and power screw transmission for EMA.

The high-fidelity models allow simulations to be performed under different operating conditions, varying the aerodynamic external force, the actuator's velocity, and temperature. Among these factors, temperature plays a key role, as it strongly influences both energy consumption and actuator behavior.

Based on the resulting efficiency maps, new simplified models have been developed, while maintaining focus on the performance of the major components for both actuators.

The proposed work enabled the evaluation of the performance of the two actuators under different conditions, highlighting their dynamic behavior and the influence of estimated efficiency on the individual actuator elements. The resulting models can be integrated into a broader aircraft digital twin within the Clean Aviation HERA project. Efficiency maps were generated starting from the available sizing data of the analyzed actuators. However, the proposed methodologies are not limited to those values and can be extended to alternative actuator architectures. From this perspective, the models are scalable and readily reusable.

Experimental Validation of an Aircraft Digital Twin: From Concept to Validation

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1. Introduction / Objectives

Although digital twins help accelerate the design process in aviation, ensuring their aerodynamic reliability remains a fundamental challenge. By focusing on the experimental validation of virtual models, this study aims to address a critical shortcoming that currently limits the broader industrial adoption of these models. In this context, a high-fidelity digital twin and a scaled physical model of a regional transport aircraft have been developed to shorten the development cycle and maximize pre-prototype design validation. The aerodynamic data measured in the wind tunnel have been compared with the virtual model data by applying scale corrections, thereby completing the model validation. While validation processes in the current literature typically rely on traditional manufacturing methods, this study presents an innovative, fast, and low-cost approach that integrates half-model wind tunnel configurations with a digital twin infrastructure.

2. Methodology

This study consists of two integrated phases: the creation of a digital twin model and the conduct of experimental wind tunnel tests. In the initial phase, a high-fidelity digital model (Figure 1) was developed using Siemens Amesim software to simulate the aircraft's dynamic behavior and subsystem interactions. During the modeling process, data on the Pilatus PC-21 aircraft found in the literature were integrated into the system as basic input parameters, subsystem connections were completed end-to-end, and control systems were defined. The system's dynamic responses were calibrated based on current empirical data, and the obtained outputs were validated to ensure the numerical model closely approximates the actual physical model with high precision.

For the physical validation phase, a 1:37 scale physical prototype has been manufactured based on the detailed CAD design of the aircraft. To maximize the utilization of the wind tunnel test chamber's cross-sectional area and minimize blockage effects during testing, the prototype was manufactured in a half-model configuration . The test model has a wingspan of 24.3 cm, a length of 30 cm, and a mean aerodynamic chord (MAC) of 0.0405 m. Wind tunnel tests were conducted in a 40×40 cm test chamber using a constant flow velocity of 30 m/s. Because the Reynolds number differs between wind tunnel test conditions and actual flight conditions, directly comparing experimental data with numerical results obtained from the Amesim digital twin leads to incorrect results. Data transformation formulas and scaling correction methods have been applied to correct this inconsistency and address the scale effect. In this step, the differences in boundary layer thickness between the scaled model and the full-scale aircraft were calculated, and deviations in the drag coefficient (Cd) were corrected using mathematical formulas. After applying the necessary extrapolation and correction procedures, the final aerodynamic data obtained were compared with the analysis data of the digital twin model, thereby completing the experimental validation of the digital model.

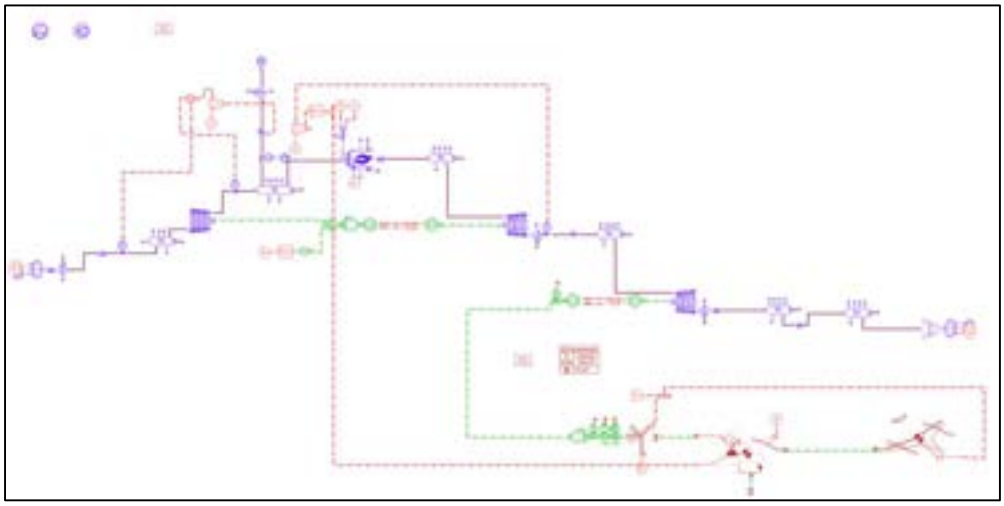


Figure 1. *Digital model.*

3. Results / Conclusions

The findings demonstrate the accuracy and reliability of the high-fidelity digital twin of the Pilatus PC-21. First, the key outputs of the digital model were validated by comparing them with existing aviation literature, and it was determined that the margin of error ranged between 5% and10%. Subsequently, experimental validation was completed by demonstrating a strong correlation between the wind tunnel data and the data expanded using the digital twin and scaling correction method. In conclusion, this approach not only accelerates system optimization and design processes but also provides a solid foundation for future aircraft development efforts.

Improving Information Supply by a Digital Design Twin for Electric Propulsion Systems

Jörg Brünnhäußer, Thomas Zimmermann, André Reißig, David Muradyan, Pascal Lünnemann, Kai Lindow

Fraunhofer Institute for Production Systems and Design Technology, Germany

1. Introduction / Objectives

The aviation industry is undergoing a fundamental transformation driven by the shift toward electric propulsion systems . This transition introduces new design challenges and demands more efficient development processes to handle the increased complexity of novel architectures. In this context, the DIREKT project aims to leverage digital twin concepts to connect and maintain information consistently along the entire product life cycle. The project seeks to overcome traditional information silos between different life cycle phases and stakeholders.

This paper focuses specifically on the design twin as a core element within the DIREKT project. The primary goal is to improve the information supply during design stages of the highly iterative development of electric propulsion systems, ultimately reducing development time and enabling faster, more informed design decisions. Specifically, we want to present a

architecture for combining different use cases and tools into a digital twin for the design phase.

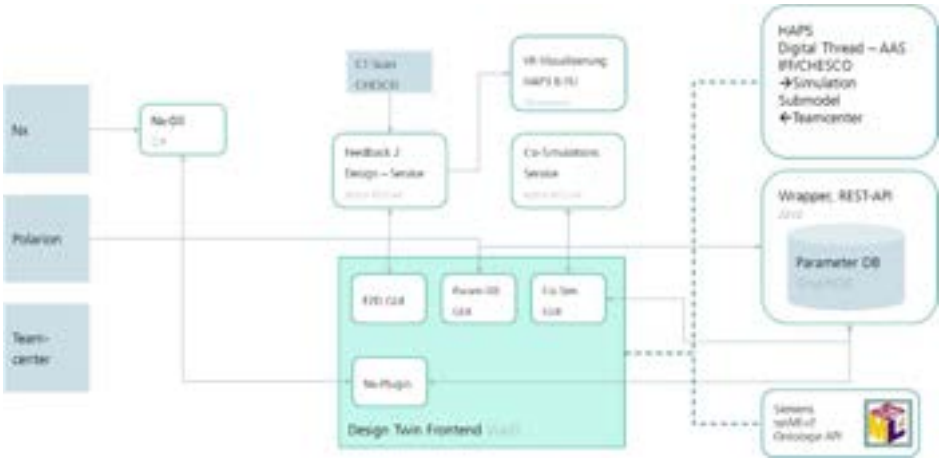


Figure 1. *Methodology for creating the digital design twin.*

2. Methodology

Based on an approach by Lünnemann user stories are gathered which serve as a user centric goal for our digital design twin, ensuring the actual usability for engineers. Then scenarios are derived, use cases are modularized and a functional architecture is drafted . Then the specific subsystems are developed and an overall IT-architecture (visualized in Figure 1.) is created for the whole system. The design twin was then developed based on microservices and a vuejs frontend. We selected high prioritized use cases like the integration of *Polarion* items, managing design parameters, estimating whether the simulation rerun is necessary and the comparison between designed and the actual manufactured part. For each user story a specific sub-system was developed and integrated into a combined architecture. A central element is the parameter database which not only manages design parameters but also connects different design and production artifacts together. Furthermore, several relevant tools are connected to the design twin, like *Polarion*, *Teamcenter* and *Nx*. The final demonstrator was deployed and tested based on each user story and whether it can be fulfilled.

3. Results / Conclusions

The initial requirements formulated as user stories are met by the developed design twin demonstrator. Based on a use case of an electric propulsion unit for urban air mobility the developed demonstrator was tested. For managing the design parameters, the parameter-database (see Figure 2.) as a knowledge graph was successfully tested according to the given requirements. Polarion was connected to enabling the connection of requirements and work items into the parameter-database. For the user story regarding the estimation whether a simulation rerun is necessary the corresponding subsystem was also tested on FMUs for an electric propulsion unit. Furthermore, the design twin provides a feature for uploading CAD files and compares them to scans of their corresponding produced parts visualizing the actual deviations due to production.

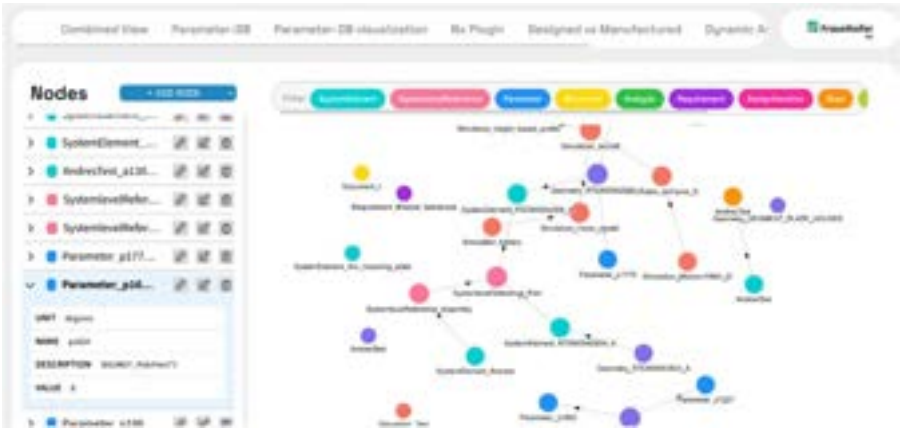


Figure 2. *Screenshot of the digital design twins web frontend showing an overview of the parameter database where design parameters are connected to geometric models which fulfills one of our initial user stories.*

Fuel Cell Propulsion System (Clean Aviation Project FAME)

Chaired by:
Dr. Kai Wicke (Airbus, Germany)

Assessment of Powerplant Technology KPI Deviations on the Conceptual Design of Hydrogen Fuel Cell Short-Range Aircraft

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University of Naples Federico II, Italy

1. Introduction / Objectives

Hydrogen fuel cell propulsion is widely regarded as a promising pathway for reducing the climate impact of short-range aviation. However, its aircraft-level feasibility strongly depends on the maturity of several powerplant-related technologies, including fuel cell stacks, hydrogen storage, air supply, thermal management, and electric powertrain components. This work is framed within WP2 of the FAME project, and in particular within the aircraft conceptual design activities devoted to the assessment of hydrogen-powered aircraft configurations. Since the achievable level of technology maturity in the next 5–10 years remains uncertain, current key performance indicators may evolve significantly before entry into service. It is therefore necessary to assess, already at conceptual design level, how deviations from reference KPI assumptions affect aircraft sizing, installed power, mass breakdown, energy consumption, and TLAR compliance. The objective is to define and apply a workflow able to quantify these aircraft-level impacts.

2. Methodology

The study is performed using the JPAD aircraft conceptual and preliminary design framework **Error! Reference source not found.Error! Reference source not found.**, developed by the DAF research group at UNINA in collaboration with SmartUp Engineering. JPAD is a modular, object-oriented toolchain implemented in Java, supporting the parametric definition and

multidisciplinary analysis of aircraft configurations. The framework includes models for mass estimation, centre of gravity evaluation, aerodynamic characterization, mission performance, environmental impact, and operating cost assessment. It combines semi-empirical methods from the literature with in-house models and time-marching performance simulations, enabling the analysis of both conventional and unconventional aircraft architectures.

For the present work, JPAD is applied to a 100-passenger hydrogen fuel cell short-range aircraft concept. The reference configuration is a propeller-driven aircraft equipped with four underwing-mounted propulsion units, each including fuel cell stacks, air supply and cooling systems, electric power management and distribution components, and reduction gearbox. Liquid hydrogen is stored in two cryogenic tanks arranged in tandem in the rear fuselage, aft of the rear pressure bulkhead.

The analysis is based on a parametric and iterative design workflow **Error! Reference source not found.**. Starting from a baseline configuration defined using the current FAME powerplant technology assumptions, selected key performance indicators are varied to represent possible deviations from the reference values expected for the assumed entry-into-service timeframe. The investigated KPIs include, among others, fuel cell stack gravimetric power density, liquid hydrogen tank gravimetric index, electric powertrain efficiencies and gravimetric power densities, as well as ancillary system assumptions related to air supply and thermal management.

Two complementary analyses are performed. First, each KPI deviation is propagated through a complete aircraft redesign process, leading to updated optimal configurations that satisfy the prescribed top-level aircraft requirements. These configurations are then compared with a baseline design to quantify the impact on aircraft sizing, installed power, mass breakdown, and mission energy consumption (Figure 1). Second, the same KPI deviations are applied to a fixed aircraft geometry, representative of the current project baseline, to assess how technological variations affect the performance margins of an already defined configuration. This dual approach allows distinguishing between aircraft-level redesign effects and direct performance penalties on a frozen design.



Figure 1. *Workflow for evaluating the impact of powerplant technology KPI deviations on the conceptual design of hydrogen fuel cell short-range aircraft.*

3. Results / Conclusions

The expected outcome of the study is a quantitative assessment of the sensitivity of hydrogen fuel cell short-range aircraft concepts to deviations in powerplant technology KPIs.

The analysis will identify which assumptions have the largest impact on aircraft sizing, installed fuel cell power, hydrogen storage requirements, and mission energy consumption. By comparing redesigned configurations with a reference baseline based on current technological KPIs of FAME, the study will quantify the aircraft-level penalties or benefits associated with each technology deviation. In parallel, the fixed-geometry assessment will highlight the robustness of the current baseline configuration with respect to uncertain technology maturation. The results are expected to support the definition of minimum technology performance targets for fuel cell systems, hydrogen storage, electric powertrain components, and ancillary systems, while providing guidance for future technology development activities and aircraft-level trade-off studies.

Wind Tunnel Validation Experiment of a Cooling Line with a Simulated HEX Device under Real Operating Conditions

Daniel Kessler[1], Jonas Grubert[1], Florian Schmidt[2], Dirk Soggeberg[2], Sebastian Merbold[2], Jens Friedrichs[1]

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[2] DLR – German Aerospace Center

1. Introduction / Objectives

The FAME (Fuel Cell Propulsion System for Aircraft Megawatt Engines) project investigates fuel cell propulsion systems for next-generation aircraft with thermal management posing a key challenge. To address this, heat exchangers (HEXs) are installed in cooling ducts inside the engine. To minimize the engine's frontal area, the heat exchangers are tilted within the cooling ducts, which increases pressure loss. The design of the cooling ducts outer shape including the HEX and its aerodynamic performance are analyzed numerically. To improve simulation fidelity, an experiment involving a propeller, nacelle, cooling air ducts, and a heat exchanger mockup is being set up in a wind tunnel. Positioning the cooling air ducts in the nacelle downstream of the propeller replicates realistic inlet boundary conditions for swirling, turbulent flow.

2. Methodology

An existing propeller is used as the basis for the wind tunnel model, scaled geometrically to a 1:6 ratio relative to the full-scale FAME aircraft as designed by . Based on this factor, quantities such as rotational speed, thrust, and others are scaled to keep the advance ratio, thrust coefficient, and related parameters consistent between the FAME aircraft and the model.

The nacelle and cooling duct are designed by DLR and scaled for the experiment . While the overall geometry is reproduced with high precision, certain modifications are necessary to meet functional requirements of the wind tunnel. In the full-scale aircraft, the electric motor driving the propeller is mounted inside the nacelle alongside the fuel-cell stacks. In the experiment, the propeller is driven by an external drive, with the shaft routed through the nacelle. Consequently, the cooling air ducts in the rear section are shifted outward to accommodate the shaft. Additionally, component wall thicknesses are increased to ensure structural self-support and to accommodate measurement hardware such as pressure taps.

No thermal dissipation occurs in the experiment; the heat exchanger serves only as an aerodynamic dummy replicating the pressure losses of the actual heat exchanger. The dummy design was determined iteratively until a configuration was found that accurately reproduced the calculated pressure loss. While perforated plates are commonly used for such purposes, their performance degrades significantly at high angles of attack due to excessive losses. Instead, profiled vanes are used to redirect the flow while reducing/minimizing additional resistance. Although only one cooling duct is instrumented, a heat exchanger dummy is installed in both cooling ducts to ensure symmetric flow. Finally, a support structure was designed to serve two purposes: positioning the model correctly within the wind tunnel and withstanding the forces of a blade-off event. The final design is shown in Figure 1.

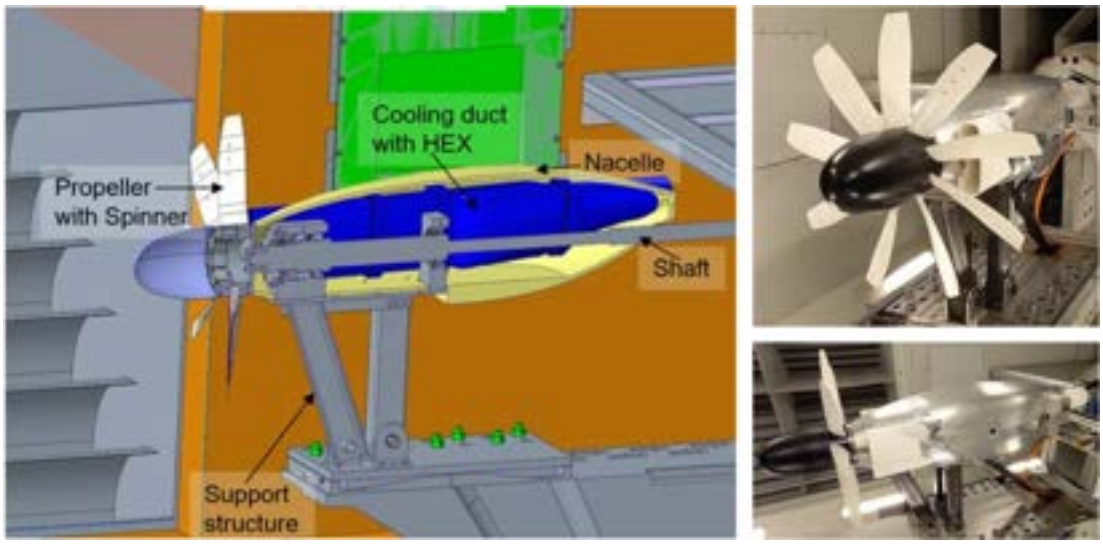


Figure 1. *Schematic of the FAME wind-tunnel model with cutaways to indicate the main elements of the propulsion system layout (left), full model inside of wind tunnel (right).*

3. Results / Conclusions

The measurements were conducted across various take-off conditions by varying parameters such as propeller rotational speed, pitch, and the inflow Mach number. Additional measurements include configurations with crosswind or without a propeller. Two measurement campaigns were conducted, providing data to validate numerical simulations. Pressure taps along the cooling duct reveal a heat exchanger pressure drop lower than predicted. Flow visualization using tufts at the cooling duct inlet indicates a flow separation driven by propeller swirl at the starting operating point, where the aircraft is stationary with no headwind. This separation disappears once headwind was introduced. Downstream of the heat exchanger, 5-hole probe measurements reveal additional flow separation caused by flow turning, the extent of which varies with operating point and vertical position within the duct.

CFD Validation of an Operating Propeller Engine with Dual Cooling Ducts

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1. Motivation

Within the Clean Aviation project FAME (GAM-101140559-FAME), a short-range, low-emission research aircraft configuration with up to 100 passengers, powered by a hydrogen fuel cell system is being development. During high-power operations such as take-off, thermal dissipation reaches up to 2 MW per engine due to fuel cell inefficiencies and power electronics losses. To ensure safe and reliable operation, an active cooling system is employed, featuring heat exchangers (HEX) integrated in a generic engine cowling. To validate Computational Fluid Dynamics (CFD) simulations of the powertrain integrated on the corresponding aircraft configuration, a dedicated wind tunnel experiment is set-up focusing on the engine cowling with cooling ducts and propeller. A simplified device is used to mimic the influence of the HEX of the flow in the cooling. With a focus on the flow in the cooling line, detailed measurements are utilized for validation purposes, while thermal aspects of heat flux are not considered at this stage. The results provide a solid understanding of the technical challenges of the cowling-integrated cooling lines and allow an assessment of the simulation quality using CFD methods.

2. Methodology

The study presents a validation of CFD against wind tunnel data where the complex flow resistance within the HEX array is modeled using the Darcy-Forchheimer porous media approach, avoiding detailed geometric resolution. The engine cowling and cooling duct geometries are adapted from the engine design by Schmidt et al. . In Fig. 1 the wind tunnel test setup at the Propulsor Test Facility (PTF) of the Institute of Jet Propulsion and Turbomachinery (IFAS), University of Braunschweig is presented. The HEXs are integrated within the cooling ducts each with an inclination of 75° to enhance sufficient thermal performance in the targeted application and accommodate compact integration within the engine. The CFD setup includes key installation components, such as support structures, engine shaft and bearing mounts downstream of the engine, support structure below the nacelle as well as wind tunnel walls, to accurately replicate boundary conditions. The experiment employed a comprehensive instrumentation suite, including static pressure probes, wall pressure taps, Kulites transducers and 5-hole probes, to resolve surface pressure distributions and three-dimensional velocity fields in the propeller slipstream within the cooling duct, enabling detailed characterization of complex flow structures such as vortices and near wall flow. For this study DLR's TAU code is applied using RANS simulations incorporating an actuator disc model to represent the propeller of the engine designed by Lenfers et. al.

3. Results

In Fig. 2 a CFD solution obtained at an rpm of 5063, the propeller's blade has been pitched to 34° and the headwind speed has been set to Mach-number of 0.15. In addition, the naming convention of the ducts, the position of the instrumented heat exchanger as well as the rotational direction of the propeller is displayed. The flow enters the cooling duct uniformly, acquiring a moderate swirl along the duct length being straightened within the, exiting the cooling duct without flow separation. The CFD results show good agreement with experimental velocity fields, confirming the model's reliability for future thermal system

optimization. This work supports the design of compact, high-efficiency cooling systems for future low-emission aircraft. For the final paper a comprehensive validation will be presented comparing static pressure distributions along the cooling duct, wall pressure at the HEX with results obtained in the wind tunnel campaign.

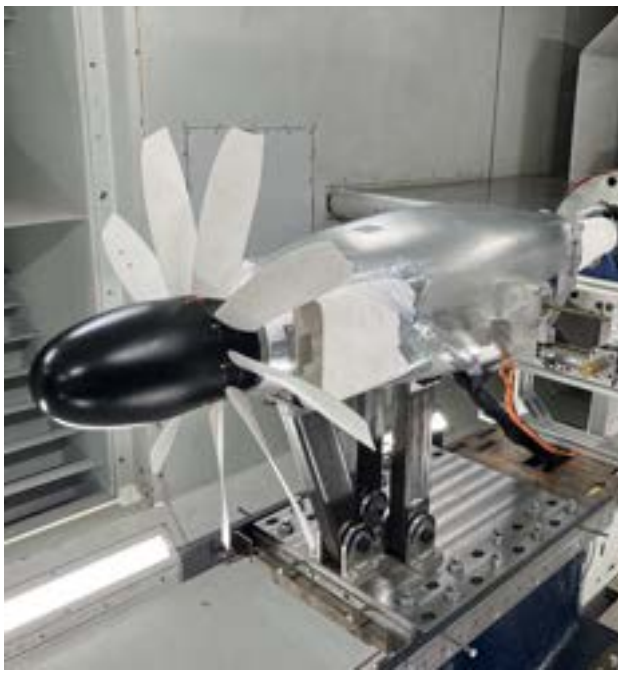


Fig. 1: *View of wind tunnel test setup at IFAS, TU BS*

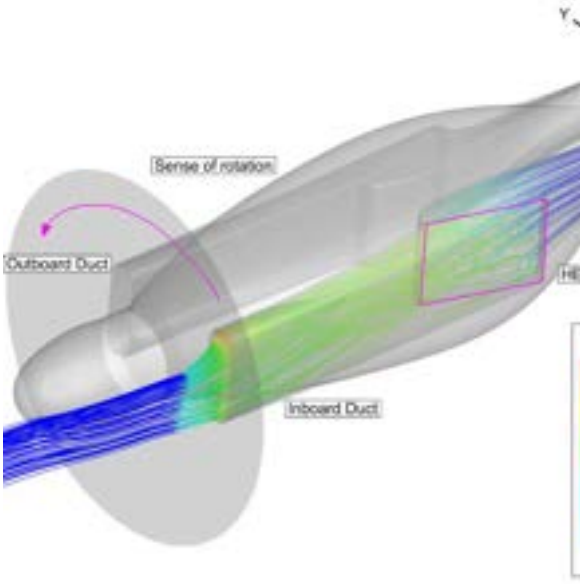


Fig. 2*: CFD solution obtained at rpm=5063, blade pitch=34° and M=0.15, with integrated HEX colored in purple*

FAME - LH2 Storage System Qualification

W. Schimpl, M. Huber, D. Hammer
Magna Steyr Fahrzeugtechnik GmbH & Co KG, Austria

1. Introduction / Objectives

The Clean Aviation–funded FAME project (Fuel Cell Propulsion System for Aircraft Megawatt Engines) aims to advance the demonstration of a fully electric propulsion architecture suitable for future aircraft applications. Within this framework, Magna contributes the complete hydrogen fuel system, encompassing liquid hydrogen storage, conditioning and distribution functions, refueling and safety systems, and the associated control architecture.

2. Methodology

The developed fuel system is conceived to support representative mission profiles with

variable operating conditions over extended durations. 150 kg of liquid hydrogen is stored under cryogenic conditions and converted into gaseous hydrogen through an integrated conditioning process, ensuring adequate mass flow (14 g/s), pressure, and temperature levels for fuel cell operation.
This contribution presents the applied qualification approach and summarizes key outcomes from the system development and test activities. The overall system architecture is primarily driven by stringent safety requirements, while detailed design solutions address structural robustness under pronounced thermal gradients.



Figure 1. *Second prototype tank under LH2 testing*



Figure 2. *Second prototype tank at attitude test*

3. Results / Conclusions

Experimental results demonstrate the capability of the system to meet operational supply demands under representative aircraft attitudes, confirm acceptable dormancy

characteristics during storage phases, and validate the implemented safety concept under defined failure scenarios.

Development for a fuel cell stack for aeronautical applications

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Aerostack GmbH, Germany

1. Introduction

One of the main Aerostack objectives is to be responsible for qualifying the fuel cell (FC) stack to meet aviation standards. The focus is on adapting the top-level fuel cell system and DO-160 certification requirements specifically for the FC stack, making them relevant and achievable at that component level. This involves defining and performing qualification test procedures (QTPs) that cover aspects like vibration, operational shock, current carrying capacity, limited/loss of cooling, reactant starvation, short circuit test, gas contamination, burst pressure and end of life activities. From all these activities, the gas contaminant with particles as a contaminant on the anode and cathode side of the fuel cell stack at ex-situ and in-situ conditions was studied and described.

2. Methodology

Tests with particles as a contaminant were conducted on the anode and the cathode side of the fuel cell one cell stack *ex-situ* and *in-situ* conditions to check for the impact on both media streams (Figure 1). The effect of particles on flow and related pressure drops, with a focus on sand or similar particles (size range from 1 to 100 µm) or classified fractions of this range (Figure 2, particle size Dv □ A0 = 2.5 µm, A2 = 9 µm, A4 = 36 µm or ashrae dusts < 2.5 µm) was investigated. An external institute is supporting the development and conduction of experimental analysis. The test bench setup for particles testing is shown in Figure 1.

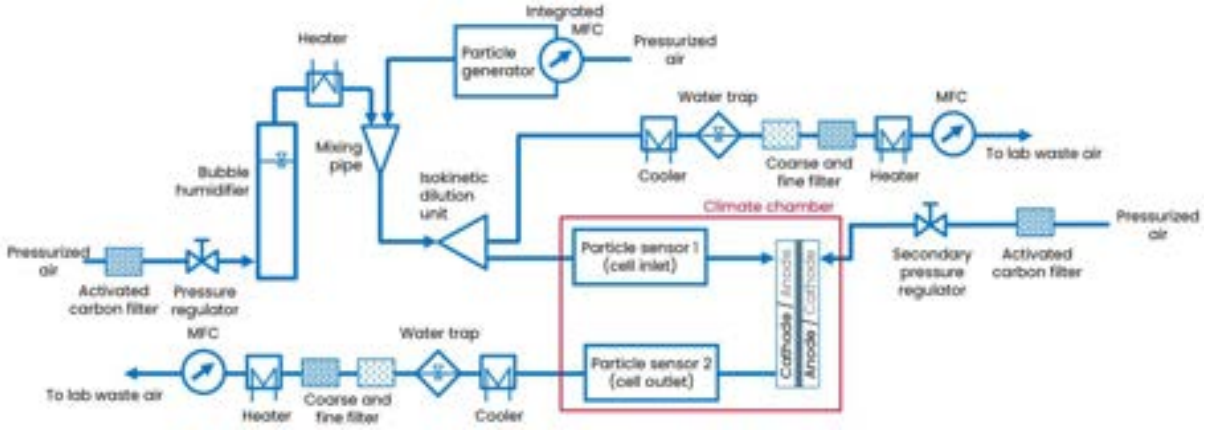


Figure 1. *Test bench setup for particles testing.*

Regarding the *ex-situ* test, the test procedure is comprised of four principal steps:

1. Particles were admitted either to the cathode or anode side

2. The single cell stack and the particle sensors were installed in a climate chamber to set the cell temperature and to avoid premature water condensation

3. The single cell stack coolant circuit is not connected

4. Tests were conducted with dry and humidified air

For the *in-situ* test, similar test procedure as *ex-situ* test was used:

1. Particles were admitted into the cathode side only

2. The 9 cells stack and the particle sensors were installed in a climate chamber to set the cell temperature and to avoid premature water condensation

3. The 9 cells stack coolant circuit was connected

4. Tests were conducted with dry and humidified air

While sending particles into the anode or cathode side of the stack, the pressure drops at the outlet of the anode or the cathode was observed and analysed with particle sensors (Figure 1).



Figure 2. *Photos of the dust particles used.*

3. Results

The tests demonstrated that higher average particle sizes lead to lower pressure drop increase due to lower stickiness of larger particles, better flowability and consequently no build-up on channel walls.
At the outlet, a significantly reduced average particle size was observed which is a result of smaller particles being more susceptible to aerodynamic forces.

Ashrae test dust causes the highest pressure drop increase as the stickiness of carbon black promotes particle agglomeration and wall deposition.
The tests with humidified air showed an agglomeration of particles due to increased moisture content and as a result increased average particle diameter and reduced particle count for respective test dust. This resulted - in line with the above findings - in a significant lower pressure drop increase.

High-Flow Liquid Hydrogen (LH2) Refuelling for Aviation: Preliminary Results and Technical Developments from the GOLIAT Project

Jean-Christophe HOGUET[1], Peter CALVERT[1], Lukas Steiger[2], David Ascic[2]
[1] Airbus, France
[2] Chart Industries, United States

1.Introduction / Objectives

Decarbonising the aviation sector, particularly for short- and medium-haul flights, requires the adoption of hydrogen as a sustainable energy carrier. However, the transition to hydrogen-powered aircraft necessitates a mature supply infrastructure and efficient daily airport ground operations. The GOLIAT (Ground Operations of LIquid hydrogen AircrafT) project, funded by the European Union, aims to overcome current technological, regulatory, and economic obstacles to enable the widespread use of liquid hydrogen (LH2) at airports. A critical challenge is the development of high-flow refuelling technologies that can meet airline requirements for turnaround times and operational costs.
This paper presents the intermediate results of the GOLIAT project, focusing on the design and development of high-flow LH2 refuelling systems. The primary objective is to demonstrate the feasibility of refuelling rates compatible with commercial aviation needs through the development of both ground-based and aircraft-based prototypes.

2.Methodology

The research follows an integrated approach across several work packages. A ground-based mobile LH2 refueller prototype is being designed and manufactured, featuring a two-unit configuration (a trailer for the tank and pump, and a separate platform for the balance of equipment). Simultaneously, a representative aircraft-based LH2 fuelling system, including a 400kg LH2 capacity tank and a specialized refuel coupling, is under development. The methodology includes rigorous safety studies, preliminary hazard identification (HAZID), and the preparation of integrated tests at the Airbus Zero Emissions Development Centre (ZEDC) in Filton, UK.

3.Results / Conclusions

Intermediate results have established a target flow rate for the refueller prototype between 5 and 7.2 tons per hour. A comprehensive feasibility study (D5.1) completed in April 2025 has given clues for the LH2 refuelling infrastructure at European airports to be

technically feasible. Furthermore, initial work on standardization and certification has identified key gaps in unified rules for mobile LH2 operations, emphasizing the need for airport-specific regulatory compliance strategies and specialized training. Detailed engineering for the refuelling system is progressing according to schedule, with the testing phase expected in Q3/Q4 2027.
The preliminary findings from GOLIAT demonstrate significant progress in mastering high-flow LH2 refuelling technologies. The defined target flow rates refuelling sequences definition lay the groundwork for the next phase of integrated demonstrations. These developments are essential to ensure that LH2 ground operations are safe, efficient, and economically viable for the future of climate-neutral aviation.

Acknowledgement: This research is sponsored by the GOLIAT project funded by the European Union (Horizon Europe) with grant agreement nr. 101138379.

LH_2 supply-cost uncertainty for H_2-powered aviation: European airport case studies

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1. Introduction / Objectives

Liquid hydrogen (LH_2) is considered one promising fuel option for achieving net-zero aviation, but its implementation requires substantial investments in dedicated hydrogen (H_2) supply infrastructure . These infrastructure decisions must be made under deep uncertainty regarding future H_2-aircraft demand uptake, renewable energy availability, technology readiness levels and H_2-market development. This results in a first-mover problem for airport stakeholders and infrastructure operators. Previous studies have mainly focused on deterministic scenario-based techno-economic analyses of LH_2 supply costs and supply pathways. The main objective of this study is to quantify a uncertainty range for airport-specific LH_2 supply costs and infrastructure requirements. The technological and scientific innovation lies in linking a mixed-integer linear optimization model (MILP) for LH_2 airport supply chains with probabilistic parameter sampling to derive cost distributions and infrastructure implications for H_2-powered aviation.

2. Methodology

A Monte Carlo-based techno-economic assessment is applied to airport case studies. The investigated time horizon covers the period from 2035 to 2055. The selected airport case studies represent different airport archetypes in terms of size, location, renewable energy availability and H_2 infrastructure readiness as illustrated in Figure 1. In addition, a dedicated cluster case is investigated, in which selected infrastructure components are jointly sized for the combined H_2 demand of two airports. Airport hydrogen demand is represented using hourly demand profiles and long-term demand ramp-up trajectories. A techno-economic optimization model for LH_2 supply chains for airports is used, based on Schenke et al. . The objective function minimizes total annualized LH_2 supply costs. The model represents the main components required to supply LH_2 for aviation, including renewable energy generation, electrolysis, liquefaction and storage, as well as the transport of gaseous and liquid H_2.

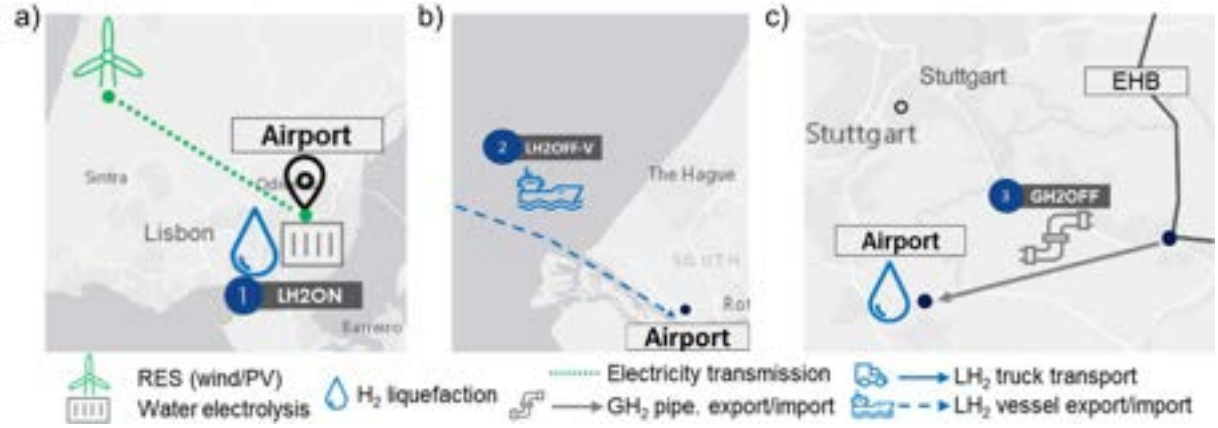


Figure 1. *LH_2 supply pathways for the investigated airport case studies: a) Lisbon Airport with on-site LH_2 production, b) Rotterdam The Hague Airport with off-site LH_2 production and vessel transport, and c) Stuttgart Airport with off-site GH_2 production and pipeline transport*

Uncertain techno-economic parameters are represented through probabilistic input distributions. Monte Carlo sampling is used to generate a large number of internally consistent techno-economic input sets for selected years. For each sample, the MILP model is solved independently. The resulting optimization outputs are statistically evaluated using probability density functions and quantile ranges to quantify airport-specific uncertainty ranges for LH_2 supply costs and infrastructure sizing.

3. Results / Conclusions

The results show that LH_2 supply costs differ substantially between airport case studies, not only in terms of median cost levels but also in terms of uncertainty ranges. Overall, LH_2 supply costs decrease significantly between 2035 and 2055, for example from approximately 12–14 USD/kgH_2 in 2035 to around 3–4 USD/kgH_2 in 2055 for Lisbon as illustrated in Fig 2. Parameter uncertainty accounts for significant variability in LH_2 supply costs. For each milestone year and airport case, the uncertainty range for airport LH_2 supply costs is between 1–3 USD/kgH_2. The results further highlight that LH_2 airport infrastructure planning should not rely on a single deterministic cost estimate or one generic airport configuration. Overall, the study demonstrates that Monte Carlo-based optimization can support more robust planning of LH_2 supply infrastructure for H_2-powered aviation by translating techno-economic uncertainty into actionable infrastructure insights.

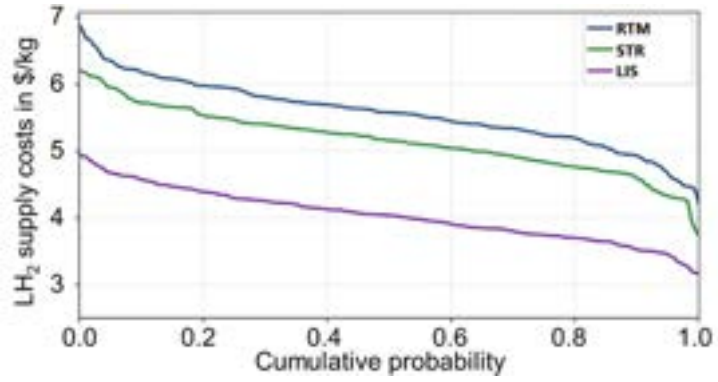


Figure 2. *Comparison of LH_2 cost ranges for the airports of the case study in 2055*

Aircraft electric powerline system architecture topology choice & optimization

M. McClelland, D. Prieto
Moteurs Leroy Somer, France

1. Introduction / Objectives

This paper describes the system architecture optimization for a multi-megawatt electric aircraft propulsion powerline. The powerline consists of an electric motor (e-motor) which drives the aircraft turbine or propellor through a gearbox and the power electronic motor control unit (inverter) as shown in Figure1. The objective of the work is to provide an overall powerline optimization to achieve lowest mass at a specified efficiency and a level of fault tolerance to allow the aircraft to continue to fly at reduced power. Design choices are described to meet the aircraft powerline specifications, as shown in Table 1, with a particular focus on fault tolerance. An e-motor gearbox optimization methodology is described. Results are presented which demonstrate state-of-the-art efficiency levels and a power density which meets or exceeds the current state-of-the-art. A comparison is made with an existing demonstrator powerline to demonstrate the scalability of the architecture to higher power levels.

2. Methodology

An architecture which uses four inverters has been selected. IGBT and SiC inverter power electronic switch topologies are compared. Several possible architectures based on four three-phase inverters are compared in terms of their fault tolerance and their impact on the number of power connections to the e-motor. Two e-motor control system models are compared in terms of their accuracy and execution time . Cross-coupled electromagnetic e-motor models are integrated to allow accurate simulation of unbalanced phase conditions to evaluate operation under different fault conditions.
Permanent Magnet Synchronous Motors (PMSMs) are the most competitive electric machines in terms of power density and efficiency . Comparisons show the Surface Permanent Magnet (SPM) motor to be the best topology to meet the aircraft requirements . Magnetization topologies (parallel, radial or Halbach) of the permanent magnet are compared with a view to reducing the mass of the e-motor. An optimization method is developed to give accurate performance and efficiency with an acceptable execution time. Pareto curves are plotted to select the best compromise between motor + gearbox mass and efficiency.
The e-motor uses a direct fluid cooled thermal architecture whereby the stator windings are immerged in the cooling fluid . Stator cooling is separated from the rotor using an airgap sleeve, made from a composite material. Cooling fluids are compared with a view to providing the best compromise between thermal performance and the electrical insulation of the motor windings. Computational Fluid Dynamics (CFD) analysis of the entire machine confirms the advantages of the proposed "direct fluid cooling" architecture compared to the existing "indirect fluid cooling,"
The gearbox is modeled using a methodology presented in the literature . This allows an

estimation of gearbox mass and efficiency as a function of the gear ratio which is the optimization parameter used for this study.

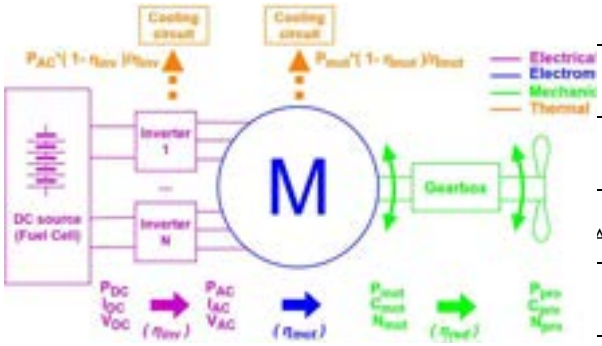


Figure 1. *Aircraft electric powerline architecture.*

TABLE I. POWERLINE SPECIFICATIONS

Parameter	Value
DC voltage (V_{DC})	800 V
AC phase/phase voltage (U_{AC})	465 Vrms
Inverter current (I_{inv})	390 Arms
Number of inverters N	4
Propeller maximum speed (N_{pro})	1000 RPM
Propeller maximum power (P_{pro})	1 MW

3. Results / Conclusions

A powerline architecture optimization has been completed with good accuracy and an execution time of less than 60s. An inverter based on a SiC, 2 level, 3 phase half bridge topology has been described. Multiple inverter modules meet the power requirement with fault tolerance. An e-motor topology has been selected. Direct liquid cooling gives a 30K reduction in hotspot temperature compared with the existing indirect cooling architecture. System optimisation leads to an e-motor design with an efficiency of 98% and a gravimetric power density of 11.5kW/kg. These values compare favorably with an existing demonstrator where the efficiency is 97% and the power density is 6.9kW/kg. The e-motor control system simulation has been developed to investigate the effect of e-motor and inverter failures at a powerline system level. This will be used in the future to evaluate the system impact of different fault conditions, such as a phase open circuit.

Novel Rejected Heat-to-Thrust Recuperation System for Fuel Cell-Electric Aircraft (exFan Project)

Chaired by:
Dr. Belén García-Blanco (CIDETEC, Basque Research and Technology Alliance (BRTA), Spain)

Evaporative Cooling with Fogging for Thermal Management of Hydrogen–Electric Aircraft Propulsion

Bernhard Gerl, Matthias Ronovsky-Bodisch, Niccolò Ferrari, Martin Berens
Technische Universität Wien, Austria

1. Introduction

Hydrogen-electric aircraft propulsion systems require effective thermal management, particularly during take-off, when elevated power demand generates substantial heat loads. This work investigates improved heat rejection in the exFan propulsion system by enhancing the air-side cooling performance of the heat exchanger through evaporative cooling with fogging. The approach exploits the conversion of sensible into latent heat in the course of water evaporation and the reduced relative humidity resulting from airflow compression in the fan stage, especially in the case of hot-day conditions.

Previous studies have shown that during hot-day take-off conditions, the required heat rejection can exceed the heat-absorption capacity of the compressed airflow, especially at elevated fan pressure ratios combined with low-temperature fuel cell systems without advanced thermal management architectures.

In this study, different operating scenarios are combined with design and off-design analyses to evaluate the potential of water injection for evaporation located between the fan and the heat exchanger, as indicated in Figure 1. The objective of the fogging system is to reduce the temperature of the compressed air upstream of the heat exchanger, thereby increasing the available temperature difference for heat rejection during critical operating phases, while evaluating the impact on pressure losses and cruise propulsion efficiency.

2. Methodology

Parametric studies are conducted in MATLAB using a turbomachinery-based approach to evaluate performance and the required heat-exchanger surface area to dissipate heat occurring in the fuel cell. The goal is to determine propulsive efficiency, including the air-side pressure loss in the heat exchanger. The analysis focuses on the interactions between fan pressure ratio, operating conditions, compressed airflow properties, and heat exchanger cooling capability across various flight and environmental scenarios.

Fan compression increases air temperature, which reduces relative humidity despite the opposing effect of pressure increase. Overall, the temperature rise dominates, creating greater potential for evaporative cooling along the airflow path. The utilization of latent heat allows for a decrease in air temperature upstream of the heat exchanger, which is especially beneficial during the take-off phase, when substantial heat loads must be rejected across a range of ambient temperatures. The aim is to reduce the required heat-exchanger air-side flow path length and the associated aerodynamic pressure losses.

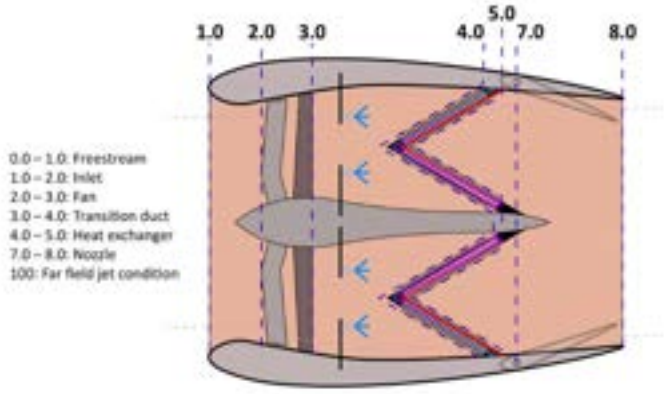


Figure 1. *exFan propulsor showing spray devices located in the transition duct (position 3-4) before the heat exchanger with the aim of reducing the air temperature of the system used to reject the occurring fuel cell heat.*

Special attention was given to hot-day take-off conditions, as such conditions are frequently associated with low ambient relative humidity. These low-humidity conditions enhance the evaporation potential of injected water, thereby increasing the possible cooling effect, making this method attractive at elevated ambient temperatures.
The methodology further includes comparative analyses of heat rejection capability, temperature difference, and pressure losses for different operating points and heat exchanger configurations. This enables an assessment of both the thermal benefits and the aerodynamic improvements associated with the proposed fogging approach.

3. Results

The results quantify the amount of water required to achieve sufficient evaporative cooling for different propulsion system design strategies across a range of fan pressure ratios. The study compares heat exchanger configurations for take-off with designs prioritizing cruise efficiency. In addition, analyses are performed under hot-day take-off conditions.
The analyses provide propulsive efficiency values for several operating points investigated across various ambient temperatures. The results demonstrate the potential of evaporative cooling with fogging to increase heat rejection capability during critical hot-day take-off scenarios while reducing the need for more complex thermal management architectures.
The investigations conclude with the identification and evaluation of the system's operational limits. Furthermore, the study highlights the trade-off between enhanced cooling performance and pressure losses within the propulsion system. The findings contribute to the development of robust, aerodynamically efficient hydrogen-electric aircraft propulsion systems.

Parametric Comparison of Heat Dissipation Architecture for Fuel Cell Electric Aircraft

Matthias Ronovsky-Bodisch, Niccolò Ferrari, Bernhard Gerl, Martin Berens
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1. Introduction

One of the key challenges to achieving climate neutral aviation is not only to design alternative propulsion systems but also to increase power to weight ratios of key system components in order to attain aircraft masses that do not negate all advantages. This is especially important for hydrogen electric propulsion systems. Improving aircraft performance and maximum take-off mass cannot be achieved solely by improving the performance of individual components and systems, but also by identifying and utilising synergies between subsystems.

One promising concept is the recuperation of fuel cell heat for additional thrust generation as proposed in the exFan project and investigated by Gerl et al. and Ronovsky-Bodisch et al. . These studies propose a ducted propulsor for a fuel cell electric aircraft consisting of an electrically driven fan and a heat exchanger installed downstream, as shown in Fig 1. Via the heat exchanger, the air passing through the duct is heated, increasing its volumetric flow rate and thus recovering the fuel cell heat as additional thrust when expanded via the nozzle. The placement of the fan upstream of the heat exchanger brings the benefit of increased pressure levels, improving the efficiency of the recuperation via the ram jet effect. The concepts proposed in and indicate significant performance advantages over conventional systems but only consider the effects on the propulsor and do not take overall system efficiency and mass into account. Therefore, the aim of this work is to investigate the impact at the aircraft level and compare it with a thermal management system (TMS) featuring a separate air duct for the heat exchanger dissipating the fuel cell heat, as shown in Fig. 2.

2. Methodology

In this work, different aircraft configurations are compared, and in a parameter stud key design parameters of the propulsion and thermal management systems are investigated and the impact on the designs is compared. The considered configurations differ in the integration of the TMS of the fuel cell propulsion system. One design only utilises the heat exchanger in the propulsor to dissipate the fuel cell heat, whereas another only uses a heat exchanger in a separate air duct, and thrust is only generated via a ducted propulsor. Furthermore, a third configuration is investigated, combining the two approaches in order to utilise the advantages of both concepts.

All aircraft configurations are based on a short to medium range (SMR) aircraft designed to carry 170 passengers and a thrust distributed across four propulsors.

The aircraft design is based on established methods by and and was expanded to include dedicated models for the design and off-design analysis of the novel propulsion and fuel cell system. With the created MATLAB model, parameter studies are conducted, varying parameters like fuel cell as well as TMS efficiencies and power to weight ratios for all investigated aircraft configurations. Furthermore, ambient conditions and sizing points for the different TMS configurations are investigated, as these have a significant impact on different hot day take-off scenarios.

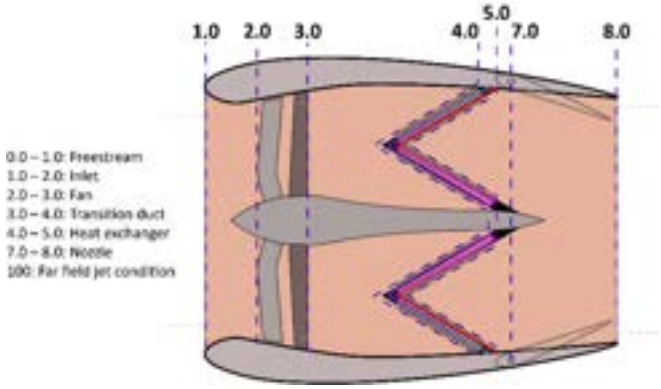


Figure 1. *Conceptual representation of the recuperative propulsion system.*

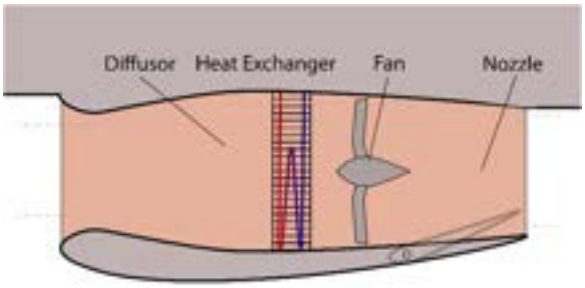


Figure 2. *Conceptual representation of a dedicated heat exchanger air duct.*

3. Results

Based on the results of the parameter study, the different configurations are compared at the aircraft level based on maximum take-off mass and overall system efficiency along a flight path. Further, the advantages and disadvantages of each configuration are discussed. The investigation provides valuable insight into the necessary performance numbers (power to weight, efficiency) of key system components in order to make the proposed propulsion concepts viable and competitive with established propulsion systems.

Integration of Compact Plate-Fin Heat Exchanger in a Ducted Fan Propulsion Systems for Hydrogen–Electric Aircraft

Niccolò Ferrari, Matthias Ronovsky-Bodisch, Bernhard Gerl, Martin Berens
Technische Universität Wien, Austria

1. Introduction

Hydrogen-electric propulsion systems based on Proton Exchange Membrane (PEM) fuel cells are a promising pathway towards decarbonising aviation. However, PEM fuel cells operate at approximately 50% efficiency, meaning that for a MW-class propulsion system, an equivalent amount of thermal power must be rejected. Effective thermal management is therefore a central design challenge.
The exFan propulsive architecture exploits the Meredith effect by integrating the heat exchanger (HX) directly within the propulsion duct, aiming to convert waste heat into thrust augmentation. Within the duct, airflow is pressurised by the fan, heated across the HX, and accelerated through the nozzle to generate thrust . Given the large amount of low-grade (low-temperature) heat rejected by the fuel cell system, maximizing HX surface area is critical. This work investigates how different inclined compact plate-fin HX integration strategies can achieve this goal.

2. Methodology

Inclining the HX, with respect to the ducted flow, offers two principal aerodynamic

advantages: first, it increases the effective air-side frontal area of the HX for a given duct cross-section; second, the inclined orientation stipulates a diffusing effect, reducing the local air velocity within the HX channels and thus potentially lowering total pressure losses.
Two integration strategies are analysed and compared:

- Conical: the heat exchanger has a cone-shaped form.
- Chevron-shaped: the HX core is arranged in successive angled segments within the annular duct cross-section, as shown in Figure.

For each configuration, a parametric study is conducted varying: the inclination angle of the heat exchanger relative to the flow direction, the axial length of the HX core, and, for the corrugated multi-pass geometry, the number of successive angled segments. A particular focus is placed on the characterisation of the "unused volume zones", defined as regions within the heat exchanger core that are not accessible to the flow due to the inclined chevron geometry within a fixed annular duct. The extent of this region is quantified as a function of inclination angle and further HX geometrical parameters.

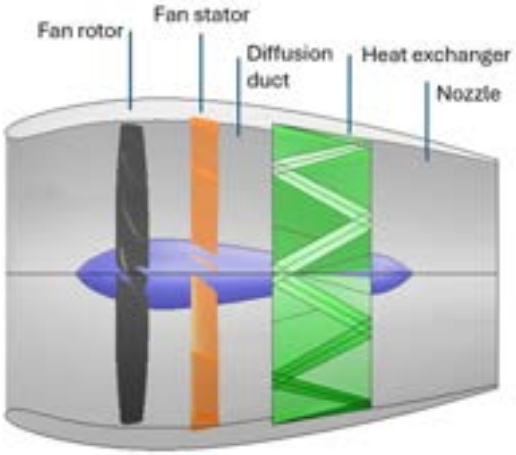


Figure 1: *Conceptual representation of the propulsion system with the Chevron-shaped heat exchanger integration*

3. Results

Results quantify the extent of the "unused volume zones", the flow-inactive region, as a function of HX inclination and geometric parameters defining the annular integration. At low inclination angles, the growth of dead zones offsets any gain in projected area, leading to negligible or even adverse performance in terms of effective heat transfer capacity. Intermediate configurations improve flow utilisation and diffusion within the HX core, reducing local velocity peaks and associated pressure losses. Overall, the results highlight a trade-off between heat transfer area and volumetric utilisation of the duct, directly affecting the compactness of the integration strategy.

Fuel Cell Thermal Management – overcoming high heat loads without oversizing heat exchangers

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1. Introduction / Objectives

Thermal management is a major bottleneck for the technical viability of fuel cell aircraft. Unlike turbofan engines, which reject waste heat through exhaust gases, fuel cell aircraft require large active heat exchangers. Heat loads strongly depend on mission profile and ambient conditions, with high power demands and temperatures up to 42°C often causing oversized thermal management systems (TMS). Current research mainly focuses on component-level optimization and stationary analysis of critical phases such as take-off and cruise using conventional air and liquid cooling, while neglecting aircraft-level impacts and transient thermal management capabilities. This paper proposes a thermal management system based on two-phase heat transfer, utilizing advanced thermal management methods (oxygen injection, power-splitting, pre-heating of liquid hydrogen as well as fuel cell heat storage/overheating and validates these strategies in a fully transient TMS model over multiple missions as well as considering effects on aircraft mass and fuel consumption. The results are part of the HEU project exFan 101138184.

2. Methodology

Objective #1: Set up a transient fuel cell and TMS model: In an initial step, sizing & performance models of the TMS components, including pumps, compressors, piping, valves and heat exchangers were developed in Matlab/Simulink. A fuel cell model was developed in Modelica and combined with the TMS Simulink model as .fmu via Matlab System Composer. Based on these models, performance maps were created to act as surrogate models within a fully transient fuel cell propulsion system model. The transient propulsion system model uses the required thrust profile and ambient operating conditions as inputs. The propulsion system operating variables are dynamically controlled to achieve the requested thrust throughout the mission profile. The baseline TMS architecture utilizes a two-phase refrigerant loop, as shown in Figure 1.
Objective #2: Evaluate Advanced Thermal Management Capabilities: To evaluate advanced thermal management capabilities, additional subsystem modules representing oxygen injection, power splitting between battery and fuel cell, hydrogen pre-heating, internal fuel cell heat recuperation and controlled fuel cell overheating were integrated into the baseline TMS model. These additional modules were used to assess their influence on the effective heat exchanger heat load, as well as the resulting aircraft system mass and fuel consumption using the WayTUFly aircraft sizing model developed by TU Wien in the exFan project.
Based on the resulting thermal and aircraft-level performance analyses, the most promising thermal management concepts were selected for integration into the exFan TMS architecture.

3. Results / Conclusions

The results presented in this article define the most promising advanced thermal

management strategies for fuel cell aircraft and their impact on TMS sizing & integration as well as the impact on aircraft mass and fuel consumption. The chosen thermal management system is capable of overcoming hot-day take-off while minimizing airside pressure losses during cruise operation. The results are valid for short-to-medium range aircraft, but an outlook on the application of other fuel cell aircraft that may be in operation earlier is given.



Figure 1. *exFan baseline two-phase TMS without additional modules*

Rethinking Fan Design: The Case for Low-Mach Integration with Heat Exchangers

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1. Introduction

The integration of heat exchangers within the flowpath of electrically driven fans challenges several long-established assumptions in fan design. Conventional single-stage fans are typically designed with fan-face Mach numbers around 0.6-0.65 , whereas efficient heat exchanger operation favours in significantly lower Mach levels (0.1-0.2) . Bridging this mismatch generally requires high levels of diffusion between these components, resulting in substantial pressure losses and reduced system efficiency. This raises a fundamental question: should fans intended for integrated heat-exchanger propulsion systems be designed differently from conventional aircraft fans? To address this question, the present work investigates the aerodynamic and system-level implications of low-Mach fan designs for integrated fan-heat exchanger propulsion architectures.

2. Methodology

The preliminary aerodynamic design is performed using the DLR in-house 2D throughflow design tool coupled with an optimization framework . A series of optimization studies is conducted to investigate the aerodynamic implications of designing a ducted e-fan for low fan-face Mach numbers ranging from 0.3 to 0.6. The optimization framework adjusts key fan design parameters, including flowpath geometry (hub and tip lines), rotational speed, and blade-row characteristics, to satisfy the performance requirements derived from the cycle design while maintaining acceptable levels of aerodynamic efficiency.
Subsequently, the fan-face Mach number is fixed and the potential to diffuse the flow within the fan stage is investigated through a second optimization campaign. The resulting trade-off between maximizing fan-stage efficiency and maximizing flow diffusion is used to assess how diffusion can be distributed within the propulsion system. The Pareto-optimal solutions provide design guidelines for fan stages integrated with downstream heat exchangers and quantify the extent to which diffusion can be shifted from dedicated duct diffusers into the fan stage itself, thereby reducing the need for complex intermediate diffuser concepts.

3. Results & Conclusions

The results show that fan optimisation for integrated heat-exchanger propulsion systems differs significantly from conventional fan design. While lower fan-face Mach numbers can improve fan-stage efficiency due to the interplay between shock losses and profile losses, the optimum system-level performance is obtained at a fan-face Mach number of approximately 0.50 due to the trade-off between intake and diffuser losses. Increasing diffusion within the fan stage reduces stator outlet Mach number and decreases downstream pressure losses, leading to an improvement in installed efficiency of approximately 2% . The study demonstrates that low-Mach fan design is a key enabler of integrated fan–heat exchanger propulsion architectures and should be considered early in the design process.

Recirculation-Assisted Surface Engineering of Complex AM Heat Exchangers in Aerospace Applications

M. Belen García-Blanco, Virginia Sáez de Viteri, Olaia Ortiz, Amaya Garcia-Casas, Asier Salicio
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1. Introduction / Objectives

Additive Manufacturing (AM) enables the production of compact heat exchangers (HXs) with highly optimised geometries and enhanced heat-transfer capabilities. However, AM aluminum components often exhibit high surface roughness and process-induced defects that can negatively affect pressure losses, fouling resistance, corrosion behaviour, and overall operational durability.
Surface post-processing is therefore essential to improve the functional performance of AM HXs while maintaining the advantages of their complex geometrical features. Among the available techniques, chemical surface treatments offer significant potential due to their ability to uniformly process intricate internal passages that are difficult to access using conventional approaches. Nevertheless, ensuring homogeneous treatment inside narrow complex flow channels remains a major challenge.
This work investigates the application of chemical polishing and electroless Ni–P coatings to AM aluminum alloys using a recirculation-assisted processing approach. The objective is to evaluate the influence of different surface preparation routes on coating quality and to assess the suitability of the resulting surface modifications for advanced aerospace thermal management applications.

2. Methodology

An experimental campaign was conducted to develop and evaluate chemical surface treatment strategies for AM aluminum alloys used in compact heat exchangers. To enable effective treatment of complex internal passages, a dedicated recirculation system was implemented, allowing continuous electrolyte flow through the components during processing.
Different pre-treatment routes were investigated prior to electroless Ni–P deposition. These included chemical polishing procedures aimed at reducing AM-induced surface irregularities, followed by zincate activation treatments to promote coating adhesion on aluminum substrates. The influence of single- and double-zincate processes was comparatively assessed.
Following surface preparation, electroless Ni–P coatings were deposited under controlled operating conditions. The effectiveness of the different treatment routes was evaluated through surface and functional characterization. Surface morphology and coating uniformity were analysed to determine deposition quality over complex geometries, while adhesion testing was performed to assess coating integrity. Wettability measurements were used to investigate potential improvements in fluid interaction and fouling resistance. In addition, thermal conductivity analyses were carried out to evaluate the influence of the surface treatment on heat-transfer performance.

The overall methodology enabled the identification of processing conditions capable of improving surface protection and functional performance without compromising the thermal requirements of AM HX applications.

3. *Results / Conclusions*

The recirculation-assisted chemical treatment approach successfully enabled uniform surface modification of AM aluminum components containing complex internal channels. Active electrolyte circulation promoted improved coating distribution and homogeneous deposition throughout the treated geometries.
The selected pre-treatment strategies strongly influenced coating adhesion and surface integrity. In particular, the combination of chemical polishing and zincate activation resulted in improved coating quality and enhanced surface protection. The treated samples also maintained thermal properties compatible with heat exchanger operation while exhibiting surface characteristics potentially beneficial for reducing fouling effects.
Overall, the study demonstrates the feasibility of applying electroless Ni–P surface treatments to complex AM heat exchangers using recirculation-based processing. The proposed approach represents a promising post-processing strategy for improving the durability and operational reliability of next-generation aerospace thermal management systems.

Advances in Hybrid-, Cryo and More Electric Aircraft Technologies for Ultra Efficient Flight

Chaired by:
Dr. Andreas Battenberg & Mr. Florian Hilpert (Fraunhofer, Germany)

Why One Battery is Not Enough: Architecture-Driven Optimisation of Propulsion, Non-Propulsion and Reserve Energy Systems in Future Single-Aisle Aircraft

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1. Introduction / Objectives

The decarbonisation of aviation is driving increasing electrification of aircraft systems in both regional and future single-aisle aircraft. Hybrid-electric propulsion concepts are being considered for both segments; however, at present, it appears unlikely that a significant degree of propulsion hybridisation will already be realised in the single-aisle generation expected around 2035. Further progress towards more-electric aircraft (MEA) architectures, by contrast, is widely anticipated.

Within such architectures, batteries are expected to become an important building block for improving overall system efficiency, in particular by supporting the management of transient electrical loads. To exploit this potential effectively, however, it is necessary to clearly distinguish between propulsion, non-propulsion, and reserve electrical functions, since these lead to fundamentally different system requirements and, consequently, different optimisation spaces.
The objective of this contribution is therefore:

(i) to establish a clear functional and architectural differentiation between propulsion, non-propulsion and reserve battery systems in future single-aisle aircraft;

(ii) to analyse the implications of this differentiation for battery system design, thermal management and integration; and

(iii) to assess the resulting safety- and architecture-driven need for dedicated non-propulsion electrical (NPE) battery systems, even in aircraft configurations that may also include propulsion batteries.

2. Methodology

The work is based on a system-level analysis combining aircraft electrical architecture considerations with battery system design principles and certification constraints.
In a first step, aircraft electrical loads are categorised into propulsion, non-propulsion, and reserve/emergency functions. Particular attention is given to NPE loads, which are typically characterised by short-duration, high-power demand profiles, for example from highly electrified onboard systems replacing hydraulic or pneumatic functions. These load profiles are contrasted with the sustained power demand associated with propulsion support.
In a second step, the resulting operational profiles are mapped to battery system requirements, with specific emphasis on:

- power capability and characteristic C-rates,
- thermal load generation over time,
- implications for battery system architecture and thermal management system sizing.

A central hypothesis of the analysis is that NPE-dominated duty cycles generate substantially lower cumulative thermal loads than propulsion-oriented duty cycles, because the relevant power peaks are brief and intermittent. This may allow the use of less complex and lighter thermal management systems, thereby improving overall gravimetric energy density at system level compared to propulsion battery systems.

In a third step, architectural integration options are assessed, comparing:

- combined battery architectures serving multiple electrical functions, and
- architectures in which propulsion, NPE and reserve functions are assigned to distinct energy storage systems and associated distribution structures.

This assessment explicitly includes safety and certification considerations such as functional independence, fault containment, availability of essential functions, and validation requirements. Within this context, reserve batteries are briefly discussed as a separate class of energy storage serving dedicated emergency functions. Alternative concepts such as thermally activated reserve batteries are considered briefly for completeness.

3. Results / Conclusions

The analysis indicates that propulsion, non-propulsion and reserve electrical functions impose fundamentally different requirements on battery design and should therefore not be treated as a single optimisation problem.
For NPE applications, transient high-power duty cycles appear to offer a distinct advantage: they can significantly reduce cumulative thermal loading and thereby enable simpler thermal management systems than would be required for propulsion-oriented battery designs. This opens a dedicated optimisation space for NPE batteries with the potential for improved system-level energy density and reduced integration penalty.
Furthermore, the results suggest that future single-aisle aircraft are likely to benefit from architecturally distinct propulsion, NPE and reserve energy systems, even if large propulsion batteries were available in principle. Such separation supports fault isolation, protects essential functions, and facilitates compliance with stringent aviation safety requirements.
Although the work is motivated by future single-aisle aircraft, the conclusions are also relevant for regional aircraft. Even where propulsion batteries are introduced earlier and more extensively, the same functional, thermal and safety arguments indicate that separate NPE battery systems may remain advantageous, or even necessary, in future electrified aircraft architectures.

On the Existence of Long-Range Hydrogen-Powered Transport Aircraft

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1. Introduction

As pressure increases over hydrocarbon resources and the climate crisis forces the aviation sector to reinvent itself, hydrogen appears to offer a promising long-term solution. This is not only due to the obvious physical advantages of hydrogen's energy density, but also because its combustion in a turbojet engine or fuel cell produces low emissions. However, many are now speaking out against hydrogen-powered aircraft, arguing that they are unsuitable for medium- or long-haul flights due to physical constraints related, in particular, due to the low volumetric density of liquid hydrogen. This paper questions the validity of this claim and proposes to estimate, at the preliminary design stage, the specific gravity ratios that could be achieved to enable transatlantic hydrogen flights.

2. Methodology

The path to decarbonizing aviation heavily relies on reducing CO2 emissions from medium- and long-haul flights. The question here is whether medium and long-range aircraft can be converted to hydrogen-powered aircraft, or whether such conversion is only possible for regional or short-haul aircraft. To resolve this question, Bréguet's formula is considered, in

which an aircraft's range is expressed as a function of its aerodynamic glide ratio, its initial and final mass, and its specific fuel consumption:

$$R = \frac{V}{g} \times \frac{L}{D} \times \frac{1}{SFC} \times \ln\left(\frac{m_{ini}}{m_{fin}}\right)$$

Given a conventional jet fuel-powered aircraft and a typical mission for that aircraft, the present method allows to determine the mass of a hydrogen-powered aircraft capable of performing an identical mission, namely carrying the same number of passengers over the same distance. It is assumed that the same flight speed and the same specific fuel consumption can be achieved. Furthermore, the aerodynamic lift-to-drag ratio is reduced by 10% so as to account for the drag penalty due to an increased fuselage volume required to carry cryogenic hydrogen.

3. Results

The method shows that there is a minimum gravimetric index below which a hydrogen-powered aircraft cannot perform the same mission as its kerosene-powered counterpart. For an Airbus A320-200, the minimum gravimetric index is only 18%, whereas it is 35% for a long-haul aircraft such as the A380-800. However, those values correspond to extremely heavy aircraft. We call *tipping gravimetric index* the gravimetric index of the cryogenic hydrogen tank for which the hydrogen-powered aircraft has *exactly the same mass* as the equivalent kerosene-powered aircraft capable of performing the same mission. The tipping gravimetric index turns out to be 31% for the A320-200 and 46% for the A380-800 (Figs. 1 & 2). Both values can be reached according to Brewer's analysis and recent studies , even when including the additional equipment required for using hydrogen on board.

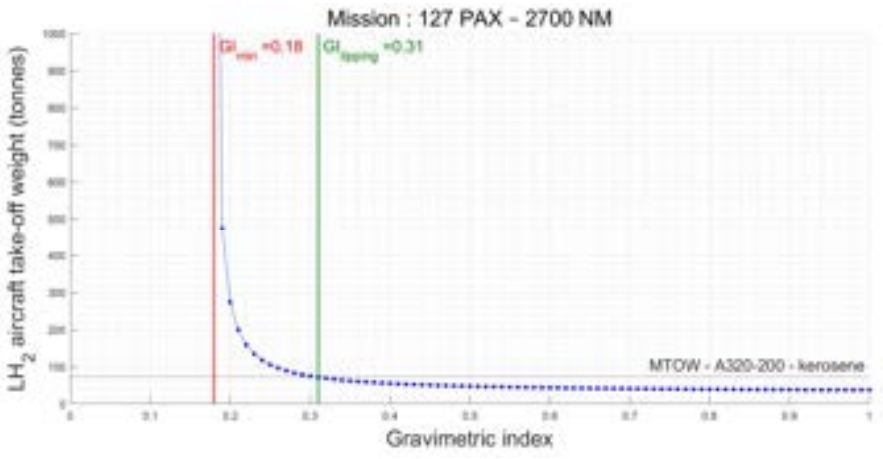


Figure 1. *Take-off mass of a hydrogen-counterpart of an A320-200 as a function of the gravimetric index.*

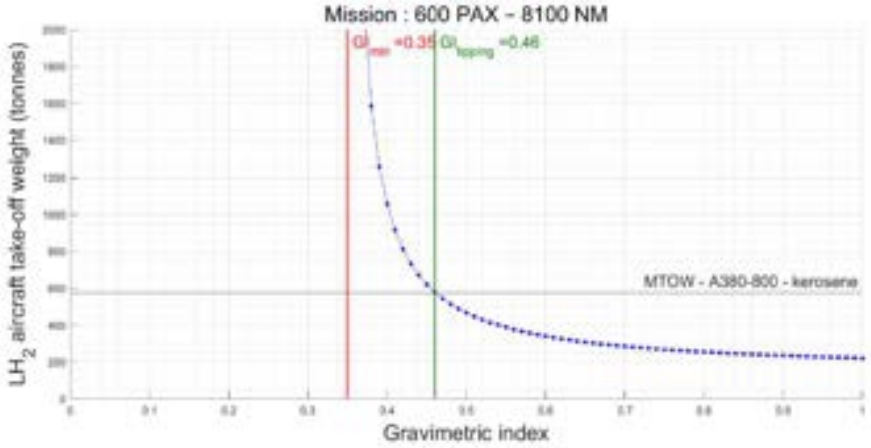


Figure 2. *Take-off mass of a hydrogen-counterpart of an A380-800 as a function of the gravimetric index.*

Beyond those tipping values, the total mass of the hydrogen-equivalent aircraft no longer decreases significantly as the gravimetric index increases, meaning that there is a target gravimetric index for each aircraft slated for replacement with a hydrogen-powered version for medium- and long-range flights. Finally, slightly lighter hydrogen aircraft may be expected for long-range flights as predicted by Brewer in the 1980s.

Implementation of a higher fidelity electrical propulsive chain in the frame of a hybrid regional aircraft multidisciplinary design analysis

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1. Introduction / Objectives

In the context of global warming and environmental urgency, the aeronautics industry is pressed to rethink aircraft design to reduce CO_2 emissions. To this end, a new generation of hybrid electric aircraft is under intense investigation across both research and industrial sectors. Potential gains are expected especially within the regional aviation sector , but the various disciplines constituting aircraft design imply a lot of interfaces to capture.
This motivated the need to develop multidisciplinary design analysis and optimization (MDAO) aircraft sizing methods. The value of these analyses, however, depends heavily on the fidelity of the integrated models. Increasing the level of fidelity across the core disciplines (aerodynamics, propulsion, mass, and geometry) is essential to provide credible assessments of the potential benefits offered by hybridization. Driven by this objective, this study aims at integrating higher-fidelity models of the electrical propulsive chain into an existing MDAO tool dedicated to hybrid regional aircraft and exploit them towards the best compromises at aircraft level.

2. Methodology

The MDAO framework used in this stud, is built upon the RTA (Regional Transport Aircraft) module, a plug-in of FAST-OAD (an aircraft sizing tool co-developed by ONERA and ISAE-SUPAERO). The regional ATR-72 was selected as the reference aircraft, and the first step of this study consisted of calibrating the conventional turboprop version of the tool against this baseline. To achieve this, the aerodynamic, weight, and geometry modules have been validated against the reference aircraft. As the original propulsion module was a polynomial surrogate model from , and did not account for some of the inputs of the reference aircraft (bleed air, Delta International Standard Atmosphere (DISA)…), it has been redeveloped using real data. A Kriging surrogate modeling approach was selected, trained via the opensource SMT toolbox. This approach enabled both engine calibration and an increased level of this discipline's fidelity. Once a fully calibrated conventional baseline was established, the hybrid powertrain was integrated. Initially, simplified power and efficiency models were implemented for the electrical chain to verify the hybridization framework. Once having a converged hybrid aircraft model, the fidelity was progressively enhanced, starting with the battery. A literature review on battery modeling reveals a clear gap: while the automotive industry heavily relies on dynamic models to capture chemistry-dependent behaviors, the hybrid aviation sector predominantly uses simplified, constant efficiency and power density parameters. These oversimplified parameters (which often assume optimistic energy densities) fail to capture essential battery chemistry, like the exponential decrease of the battery's voltage at low state of charge (SoC) for example. This study addresses the need to model specific discharge characteristics to keep track of battery indicators such as the SoC and state of health. Consequently, literature-based battery discharge curve models were implemented. Future work will extend this fidelity enhancement across the powertrain by integrating detailed electric motor and converter models developed in the HASTECS project, and then integrated in another FAST-OAD framework.

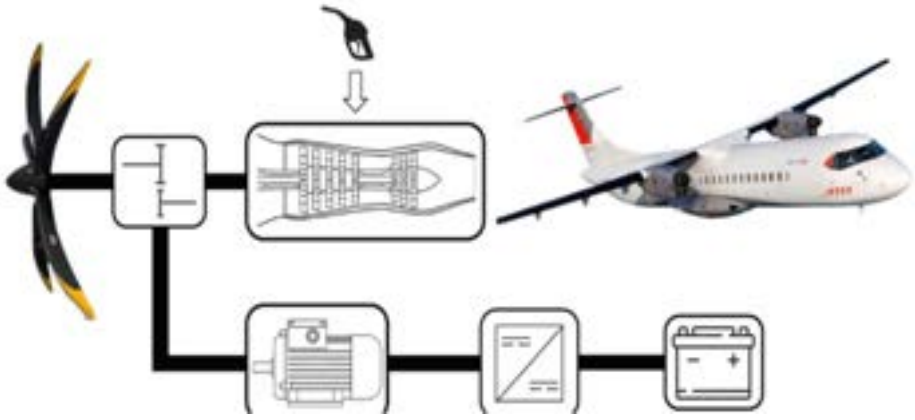


Figure 1. *Schematic of a parallel hybrid propulsive chain proposed for this regional aircraft study (ATR-72).*

3. Results / Conclusions

In summary, this study successfully delivers an aircraft sizing tool calibrated against the ATR-72 baseline, which was subsequently enhanced with a hybrid powertrain framework. Furthermore, higher-fidelity components were integrated into the electrical propulsive chain, focusing specifically on battery, electric motor, and converter modeling. Current investigations are focused on assessing how these higher levels of fidelity influence predicted CO_2 emission reductions, while evaluating the overall feasibility of hybrid-electric propulsion technology for regional aircraft. This will ultimately enable to determine optimal combination of aircraft architecture and energy management for such family of hybrid electric aircraft.

Design, performance and modelling of an electrical system for a hybrid GT-SOFC propulsion system for commuter aircraft

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Cranfield University, UK

1. Introduction/Objectives

The aviation industry aims to cut greenhouse gas emissions and achieve the goal of net-zero emissions by 2050. Hydrogen and electrical power system are promising candidates for this target, but the low power density limits their application. However, we can demonstrate their potential with a hybrid engine design that is partially powered by electricity. In our project, a hybrid hydrogen propulsion system incorporating solid-oxide fuel cell (SOFC), electrical power system and hydrogen gas turbine has been developed. While this paper focuses on the design, modelling and performance analysis of the electrical system including motor, inverter, converter and distribution system. Unlike the previous studies that usually provide a single design, our study also looks at changes in motor design with respect to varying requirements, as the designs are not always scalable. A design space exploration of electric motors is included to provide guidance for future design.

2. Methodology

Multi-fidelity modelling is the main method throughout the process. The low-fidelity, namely analytical model, usually consists of empirical mathematical equations, serves to connect requirements to basic design parameters. High fidelity models are detailed designs implemented in finite element analysis tools. It helps to analyze and evaluate the electric, magnetic and mechanical properties, and provides numerical performance maps of the components. The medium fidelity model is mathematical equations capturing more details, aiming to characterize the effect of different technologies. This results in a simple yet relatively accurate model, enabling easy integration and fast simulation of the whole system. The motor design varies greatly under different power / torque demand, installation envelope and power density targets. A design space exploration on existing designs and available technologies helps to understand the design philosophy. Design exploration gives lists of topologies, design parameters and technologies with corresponding pros & cons, cost and boundaries. Their effects on performance can be characterized and compared via the medium fidelity model. The whole design process includes:

1) geometry definition

2) move to the FEA tool to define all the details and generate performance maps

3) results from FEA tool serves to generate and validate the medium fidelity model for fast simulation

The design of the inverter and converter only have low fidelity and high-fidelity model. Empirical equations or fixed efficiency are employed for low accuracy simulations. The high-fidelity modelling includes requirements-based design, component selection and implementation in a MATLAB Simulink environment. The inverter also requires the motor's performance map to realize field-oriented control. And the converter employes cascaded voltage-current PI control algorithm. Parameters of components are calculated from empirical equations. Then, the parameters and performance indices of selected electrical components will be captured in Simulink blocks. With control algorithms implemented, the performance / efficiency map of inverter and converter can be obtained. As no FEA tools are involved, the weight and size of them need manual calculation.
The distribution system is represented with resistors in the model. The resistance, weight and length of cables are calculated from the mechanical design. Relay protection strategies are also implemented.
Analysis of the whole system involves the matching of all the efficiency maps.

3. Results and Conclusions

One of the results is a detailed design of 500 kW level electrical propulsion system. The considerations include operation / environmental constraints, installation envelopes, available technologies and cost. The details include architecture, topology, geometry, design parameters, materials, component selection and control algorithms.
Another outcome is the design exploration of electrical motors. The requirements dominate the design process, while under specific constraints, some design parameters are more suitable. Novel technologies bring further advantages at extra cost; their cost-effectiveness is also evaluated. The design exploration extends the scope of this study from commuter hybrid aircraft to future full electric short / medium range aircraft. The knowledge gained from this study not only converges to a single design, but also acts as a guidance for future electric propulsion system development.

Acknowledgement: This research has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101138488 and by the UK Research and Innovation (UKRI) funding guarantee under the project reference 10106893.

Modelling and Optimization of a UAV Parallel Hybrid-Electric Propulsion System

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[2]Instituto Superior Técnico (IST), Portugal

1. Introduction

The growing demand for more efficient and environmentally sustainable aerial platforms has accelerated the development of Hybrid-Electric Propulsion Systems (HEPS) for unmanned aerial vehicles (UAVs). This work focuses on modelling and evaluating a parallel hybrid-electric propulsion architecture, combining an internal combustion engine (ICE) with an electric motor (EM) to improve endurance, reduce fuel consumption, and enhance operational flexibility. A key contribution of this thesis is the simplification of complex dynamic models, which significantly reduces simulation time, enabling extensive mission-level analysis . The main objective is to determine the optimal hybridization level and assess the performance of different power-sharing modes across realistic mission profiles.

2. Methodology

The methodology integrates a literature review, system modelling, and simulation using MATLAB/Simulink. The UAV model includes aerodynamic and propulsive characteristics adapted from existing simulation frameworks . The propulsion system incorporates ICE performance maps, a simplified PMSM electric motor model that removes fast electrical dynamics to improve computational efficiency , and a Li-Po battery model with SOC estimation.

To evaluate the behaviour of the hybrid system under different operational conditions, six distinct modes of operation were defined. The first mode relies exclusively on the internal combustion engine, serving as the baseline thermal configuration. The second mode uses only the electric motor, enabling low-noise or low-power operation. The third mode employs the ICE as the primary power source while the electric motor provides additional torque during phases of increased demand. In contrast, the fourth mode places the electric motor as the main propulsion source, with the ICE supplying supplementary power when required. The fifth mode distributes power between the ICE and EM according to a predefined sharing ratio, representing a conventional power-split hybrid strategy. Finally, the sixth mode introduces dynamic hybridization, in which the power distribution between ICE and EM is adjusted in real time to maximize efficiency throughout the mission.

These six modes were tested across representative mission profiles, including endurance, surveillance, flight path angle change, and dash. Performance was assessed using metrics such as endurance, range, fuel consumption, and power availability, allowing a comprehensive comparison of the hybridization strategies and their suitability for different operational scenarios.

3. Results

The results show that the different operation modes lead to distinct performance levels across the mission profiles. The third and fifth modes provided the best balance between efficiency and versatility, consistently outperforming the first mode, which relies solely on the ICE and was unable to supply the required power in demanding phases. In the endurance mission, the third mode achieved the longest range and flight time, confirming the benefits of

combining the ICE with electric assistance. The fourth mode, which places the EM as the primary source with ICE support, showed improved responsiveness in moderate-demand segments but lacked the sustained power required for more intensive phases. The sixth mode, applying dynamic hybridization, demonstrated strong adaptability by adjusting power distribution in real time and improving overall efficiency. The simplified modelling approach also reduced simulation time significantly, enabling broader mission-level analysis and reinforcing the potential of parallel HEPS for UAV applications.

Transient operation of a multi-stack fuel cell system for hybrid-electric regional aircraft

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1. Introduction / Objectives

Enhancing the degree of electrification of the main propulsion system is seen as one approach to increase efficiency and reduce pollutant emissions of regional aircraft . Among the many proposed concepts for more and all-electric aircraft several hybrid approaches are discussed considering different parallel and serial architectures as well as different energy supply systems based on batteries and hydrogen-fuel cells . The EU Clean Aviation project AMBER aims to develop a parallel-hybrid propulsion system with a total power of around 2 MW. The electric powertrain is based on polymer electrolyte membrane fuel cells fueled with hydrogen.

2. Methodology

One key technology brick within the AMBER project is the fuel cell system, which provides the electrical power to the e-drive supported by an auxiliary battery. A multi-stack fuel cell system with up to 850 kW power is experimentally investigated in order to characterize the electrical output under different operating conditions and to validate the functionality of the powertrain system. The fuel cell system architecture is illustrated in Figure 1.

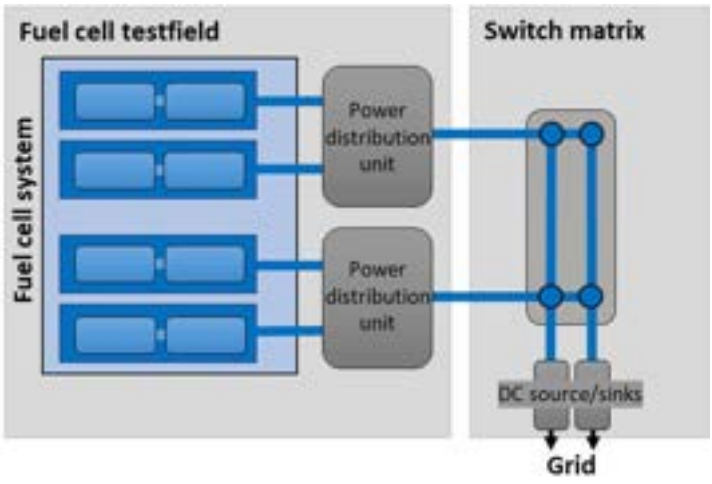


Figure 1. *Illustration of the architecture of the multi-stack fuel cell test system.*

It consists of 8 commercial fuel cell modules in a 2-serial x 4-parallel configuration. The parallel connection of the serial strings is realized without the integration of a DCDC converter via the facility infrastructure using two power distribution units and the so-called switch matrix . The direct parallel connection of the strings can lead to a large variance in the current distribution especially in dynamic operation. In order not to exceed the current limit of the individual stacks, the limitations of the system performance are to be characterized carefully. Hence, in this presentation focus is put on the transient tests of the test campaign. The system behavior is examined at various constant load ramps from idle to near maximum power and vice versa. Afterwards, representative engine transients for different typical regional turboprop flight profiles are investigated.

3. Results / Conclusions

The tests under constant load ramps showed, that a maximum current ramp of 160 A s^{-1} is achievable, which is 20 % below the theoretical limit. Hence, power ramping from idle power to 800 kW lasts at least 8 s in the proposed system. The applied load profiles for representative engine transients covered the simulation of all relevant flight phases. In all tested scenarios, the fuel cell system was able to deliver the required electrical power without any instabilities or failures. The tests suggest that converter-free multi-stack fuel cell systems can fulfil the dynamic requirements of a hybrid-electric drive for regional aircraft. However, the dynamic behavior in the combined hydrogen-fuel cell e-drive system is yet to be validated, which requires the interconnection of the entire high-voltage system. Furthermore, the altitude-capability of the fuel cell system is not yet given, which must be taken into account in future developments.

Sizing and integration of HT-PEMFC and thermal management systems on a 19-pax aircraft featuring a hydrogen-powered hybrid-electric powertrain

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1. Introduction / Objectives

Hydrogen is a promising long-term pathway to reduce aviation climate impact, with current research addressing direct H_2 combustion, fuel-cell (FC) propulsion, and hybrid combinations of the two. The work carried out in the TRIATHLON project studies a hybrid powertrain combining H_2-fuelled turboprops with high-temperature PEM fuel cells (HT-PEMFC), designed for a 19-pax regional aircraft concept by Safran Group . HT-PEMFCs are especially relevant for aircraft integration because their elevated operating temperature can improve heat-rejection margins, reduce water-management complexity, and increase waste-heat quality . The goal is to size the FC and thermal-management systems and quantify aircraft-level KPIs, including system mass, efficiency, parasitic electrical power, rejected thermal power, and drag, as functions of FC power split and key design parameters.

2. Methodology

The study adopts a multi-fidelity, model-based workflow (see Figure 1) linking cell-level electrochemical modelling, stack sizing, FC system-level modelling, thermal-management design, and aircraft-integration assessment. First, an analytical HT-PEMFC polarization model

is defined and validated against representative cell data. The model accounts for reversible voltage, activation, ohmic, and concentration losses, and is implemented in an in-house tool to perform sensitivity analyses on operating temperature, pressure, and other cell design parameters. This methodology is aligned with recent aircraft fuel-cell system studies, where pressure- and temperature-dependent polarization curves are used to propagate cell-level behaviour to stack and system-level KPIs . The fuel-cell stacks are then sized at Top-Of-Climb (TOC), while Hot-and-High Take-Off (HHTO) is used as a critical off-design condition for the thermal-management system because of the reduced temperature difference between coolant and ambient air. This sizing logic is consistent with recent HT-PEMFC aircraft assessments , where TOC drives stack and cathode-compressor sizing, while HHTO drives ram-air TMS sizing. The stack heat load, coolant temperature difference, and coolant mass-flow rate are used to design a liquid-cooling loop, radiator, and ram-air thermal-management system. The radiator and ram-air duct are sized using in-house preliminary design tools, while aircraft integration is investigated through CFD simulations in Ansys Fluent to estimate local pressure recovery, pressure drop, heat-exchanger installation effects, exhaust thrust recovery, and net drag. The CFD outputs are then fed back to an MBSE approach in MathWorks Simscape to improve the fidelity of the powertrain assessment. The workflow also evaluates mass and heat-stream synergies, including possible use of fuel-cell waste heat and transient thermal inertia from taxi to cruise.

3. Results / Conclusions

The work delivers an integrated workflow for the preliminary design of aeronautical HT-PEMFC systems and their ram-air thermal-management architecture. The expected results quantify how fuel-cell power split affects stack size, radiator area, coolant-loop requirements, parasitic electrical power, and installation drag. Preliminary sizing trends indicate that HHTO can become the limiting case for radiator design, making it challenging to exceed a 20% FC contribution on total shaft power at take-off without additional mitigation, such as thermal buffering, optimized ram-air ducts, or revised operating strategies. The study supports aircraft-level trade-offs between hybridization benefit and thermal-integration penalty, providing design guidance for hydrogen hybrid-electric regional aircraft within TRIATHLON.

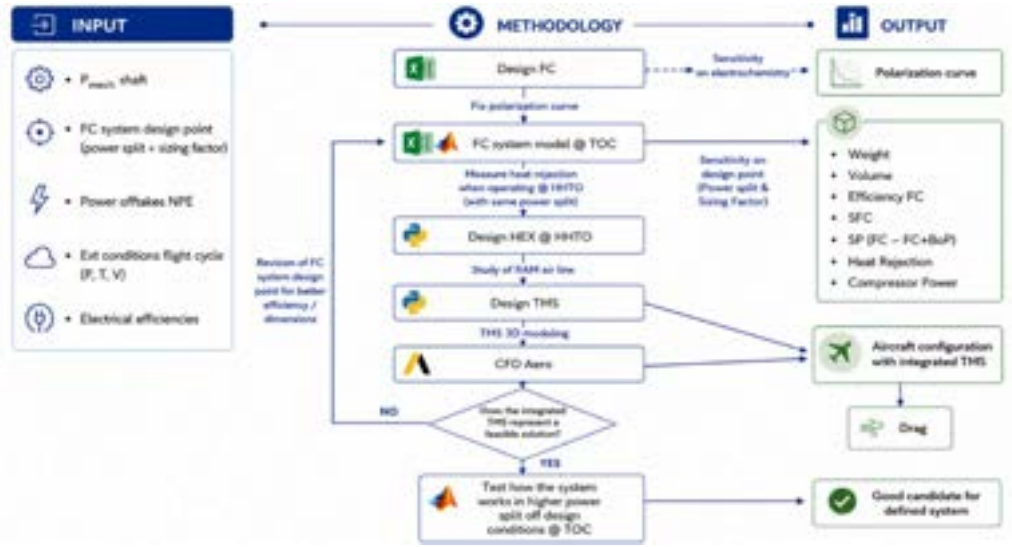


Figure 1. *Design workflow.*

Acknowledgement: This project has received funding from the European Union's Horizon Europe Research and Innovation programme under grant agreement No 101138960, project TRIATHLON.

Optimization Potential of Altitude-Adaptive Control Strategies for PEMFC Systems

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1. Introduction / Objectives

The integration of polymer electrolyte membrane fuel cells (PEMFCs) into aircraft propulsion systems is a promising pathway toward aviation decarbonization. High-altitude operation, however, subjects PEMFC systems to combined low-pressure and low-temperature conditions that significantly reduce the net power output .
While the effect of reduced ambient pressure on PEMFC performance has been investigated in prior studies, e.g. , the systematic influence of ambient temperature, which decreases with altitude according to the International Standard Atmosphere (ISA) , has received limited attention. This work addresses that gap by presenting a comprehensive experimental characterization of a PEMFC system operated under combined altitude-representative pressure and temperature conditions. The primary objective is to quantify the optimization potential of altitude- and load-adaptive control strategies in terms of net system power output, and to attribute altitude-related performance losses to specific physical mechanisms through a semi-empirical system model.

2. Methodology

The experiments are conducted on the ATLAS (Altitude Test chamber for Low-pressure Analysis of fuel cell Systems) testbed, which enables independent control of both ambient pressure and temperature inside the test chamber [see Fig. 1(a)]. The fuel cell system comprises a self-humidifying Hydrogenics HyPM HD 10-120 PEMFC stack with 120 cells, an active cell area of 195 cm², and a nominal gross power of 12 kW, complemented by a cathode air blower, an anode recirculation pump, and a coolant pump.

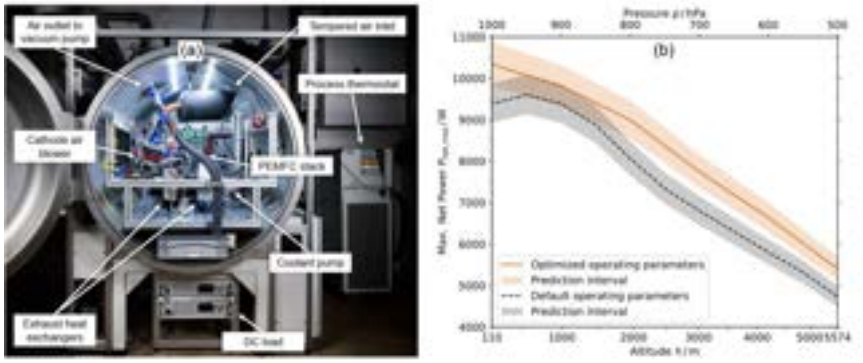


Figure 1. *ATLAS testbed with open chamber door (a). Model predictions for maximum net power as a function of altitude under ISA-representative conditions, comparing optimized and default operating parameters (b).*

The system is operated inside the test chamber at ambient pressures between 500 and 1000 hPa, with blower inlet temperatures spanning from −30 to 40 °C, combined with systematic variations of the stack temperature, the cathode stoichiometry, and the average cell voltage. For the parameter study, an I-optimal design of experiment is employed, combining 193 new measurement points with 473 points of a preceding study , yielding a total dataset of 666 steady-state operating points.
Two complementary modeling approaches are pursued. First, a purely empirical polynomial response surface model of the system net power is fitted by ordinary least squares to the combined dataset. Second, a semi-empirical system model is developed, comprising a physics-based electrochemical stack model coupled with balance of plant sub-models.

3. Results / Conclusions

Optimization of the empirical net power model yields pressure-, temperature-, and load-dependent optimal control functions for the stack temperature and the cathode stoichiometry. The results show that performance losses due to low ambient pressure dominate over those caused by low ambient temperature. However, the higher air density at low temperatures leads to a non-negligible decrease in the required cathode air blower power, positively affecting the system net power.

Fig. 1(b) shows empirical model predictions for the maximum net power as a function of altitude under ISA-representative conditions. The optimized operating parameters consistently yield higher net power across the entire altitude range, with a preliminary net power increase of 14.2 % at 5574 m (500 hPa, −21.2 °C) compared to the net power output obtained by applying the default operating parameters given by the manufacturer. Moreover, the semi-empirical model provides additional physical insight by attributing individual performance changes to specific component-level mechanisms, enabling model-based diagnostics beyond the capability of purely empirical approaches. Both model results as well as the experimental validation demonstrate large optimization potential through altitude-adaptive control for PEMFC systems in aviation applications.

Scalable Integrated Power Electronics for Fuel Cell Regional Aircraft

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1. Introduction

Hydrogen-powered fuel cell propulsion systems are considered a key enabling technology for future zero-emission regional aviation. However, current aviation fuel cell systems remain below 1 kW/kg due to the additional mass of balance-of-plant (BoP) components, cooling systems, compressors, electrical interfaces, cabling, and power electronics, despite stack-level power densities of up to 5 kW/kg. Future improvements, therefore, increasingly depend on intelligent system integration rather than solely on further stack optimisation to achieve fuel cell system power densities beyond 2 kW/kg.
Within the Clean Aviation project NEWBORN, a 1 MW hydrogen-electric propulsion demonstrator is being developed to validate fuel cell systems, power electronics, and HV-DC architectures and to derive lessons learned for future integrated and scalable regional aircraft propulsion systems.

2. Methodology

The presented work builds upon earlier aircraft-level investigations from projects such as GENESIS, which analysed hybrid-electric regional aircraft and hydrogen propulsion concepts. Within projects such as NEWBORN, HyPoTraDe, and AMBER, Fraunhofer IISB develops and validates technologies that enable the transition from conceptual propulsion architectures to experimentally verified subsystem solutions.

The methodology combines aircraft system analysis, converter development, subsystem integration, laboratory testing, and demonstrator validation. Emphasis is placed on the interaction between fuel cell systems, batteries, power electronics, auxiliary systems, and HV-DC electrical distribution networks under highly dynamic aircraft operating conditions.

Fraunhofer IISB develops scalable and redundant HV-DC architectures, lightweight DC-DC converters (>20 kW/kg), inverter systems (>18 kW/kg), electric motors (>8 kW/kg), compressor drives, and integrated control concepts for megawatt-class hydrogen-electric propulsion systems .

Instead of one large centralised fuel cell system, the investigated architecture uses multiple smaller modular fuel cell subsystems with dedicated DC-DC converters and standardised HV-DC interfaces. Depending on aircraft type and propulsion demand, these systems can be integrated into propulsion nacelles or wing sections. This distributed approach improves redundancy, maintainability, thermal integration, and installation flexibility while reducing cabling effort and overall system complexity.

Initial prototype components have already been realised and tested within Clean Aviation projects. Current integration tests focus on stable HV-DC bus operation and interaction of interconnected converter systems under representative operating conditions.

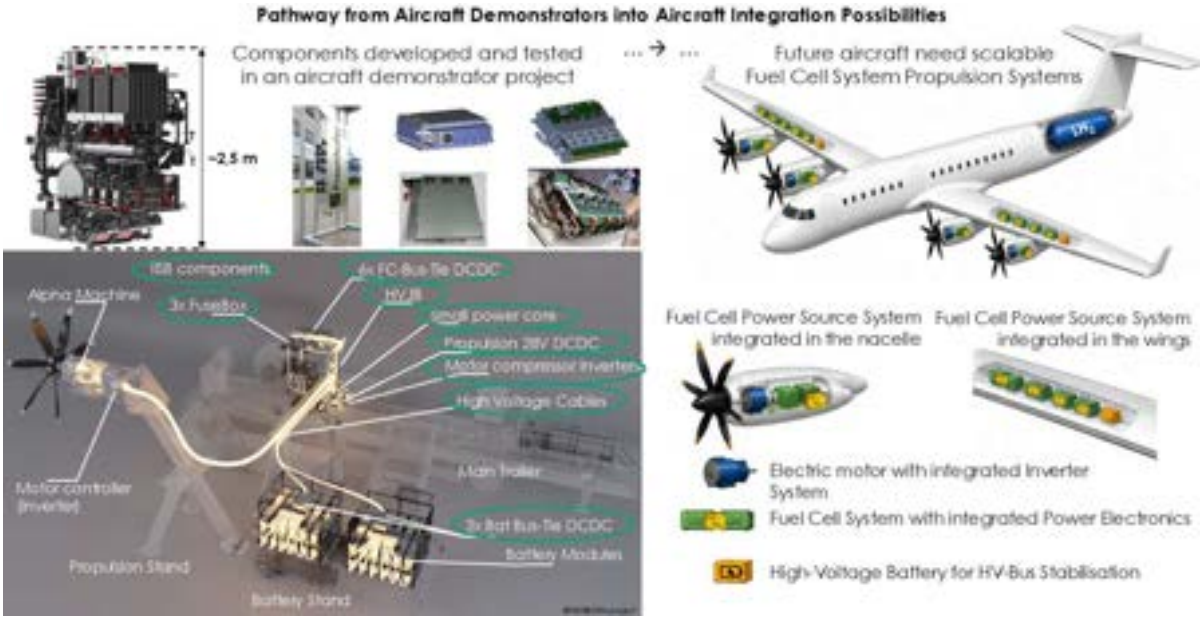


Figure 1. *Pathway from aircraft demonstrators into aircraft Integration Possibilities.*

3. Results / Conclusions

The presented work demonstrates the transition from conceptual aircraft studies toward experimentally validated megawatt-class propulsion and HV-DC distribution technologies within the NEWBORN demonstrator environment. Initial prototype and integration tests

already confirm stable HV-DC operation and successful interaction of interconnected power electronic subsystems under representative operating conditions.
The results indicate that future hydrogen-electric aircraft will increasingly depend on intelligent integration of power electronics, electrical distribution systems, and BoP components rather than solely on further stack-level optimisation. Distributed and scalable fuel cell architectures offer significant potential to reduce system mass, cabling effort, installation volume, and cooling demand while improving redundancy, controllability, and flight integration capability for future regional aircraft platforms.

Enhancing Reliability of Electric Aircraft Power Systems: A Study on Silicon Carbide and Gallium Nitride Power Devices Under Radiation Exposure

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1.Introduction

The rapid transition toward More Electric Aircraft (MEA) architectures necessitates the adoption of silicon carbide (SiC) and gallium nitride (GaN) power devices to meet stringent power density and efficiency requirements. However, operating these devices at high altitudes exposes them to a unique radiation environment dominated by atmospheric neutrons. While total ionizing dose (TID) and displacement damage (DD) are the primary reliability bottlenecks for space-grade power electronics , their impact on wide bandgap (WBG) devices in aviation remains secondary due to the higher displacement thresholds of SiC and GaN and the relatively low cumulative dose rates at subsonic and supersonic flight altitudes. The primary objective of this study is to demonstrate that single-event effects (SEE), specifically single-event burnout (SEB), constitute the dominant radiation-induced failure mechanism for aeronautical power stages. This work focuses on the evaluation of aircraft powertrain reliability that prioritizes stochastic neutron-induced catastrophic failures over long-term cumulative degradation, focusing toward altitude-dependent safe operating area (SOA) characterization.

2.Methodology

This research study employs a multi-faceted approach combining high-fidelity experimental analysis in previous literature and analytical modeling to evaluate the vulnerability of SiC and GaN power devices across the atmospheric radiation spectrum. The methodology begins with the characterization of the atmospheric proton and neutron flux at typical cruising altitudes (6-18 km) using established models such as the Professional AviatioN DOse CAlculator (PANDOCA) software developed by the German Aerospace Center . To assess cumulative effects, the study utilizes non-ionizing energy loss (NIEL) scaling to calculate the displacement damage equivalent in SiC lattices, comparing the results against the displacement threshold energy (E_d) of the material (E_d in SiC and GaN is 2-3 times that of Si). TID vulnerability is evaluated by evaluating models of charge trapping kinetics in the SiO_2 gate oxide under the low-dose-rate conditions characteristic of flight profiles .
The core of the analytical effort focuses on SEE sensitivity. The investigation prioritizes experimental evidence regarding SEB and single-event gate rupture (SEGR), which are

identified in the literature as the dominant failure modes for WBG power devices . By analyzing reported data from heavy-ion testing, the study identifies the linear energy transfer (LET) thresholds and particle flux required to trigger localized thermal runaway and parasitic bipolar junction transistor (BJT) activation in SiC metal-oxide-semiconductor field-effect transistors (MOSFETs). These findings are then correlated with neutron irradiation studies to assess the probability of SEEs at aviation altitudes.
Crucially, the methodology involves a comparative assessment between these stochastic events and cumulative damage reports. Experimental data on TID and DD from literature are analyzed to confirm that parametric shifts, such as threshold voltage drift (V_{th}) or leakage current increases, remain negligible under aviation dose rates. By contrasting the robust tolerance of WBG materials against cumulative effects with the experimentally verified vulnerability to instantaneous neutron-induced failures, this work establishes a data-driven hierarchy of reliability, as highlighted in Figure 1, modified after . This methodology serves as the basis for defining new SOA and voltage derating protocols essential for the future certification of electric aircraft power systems.

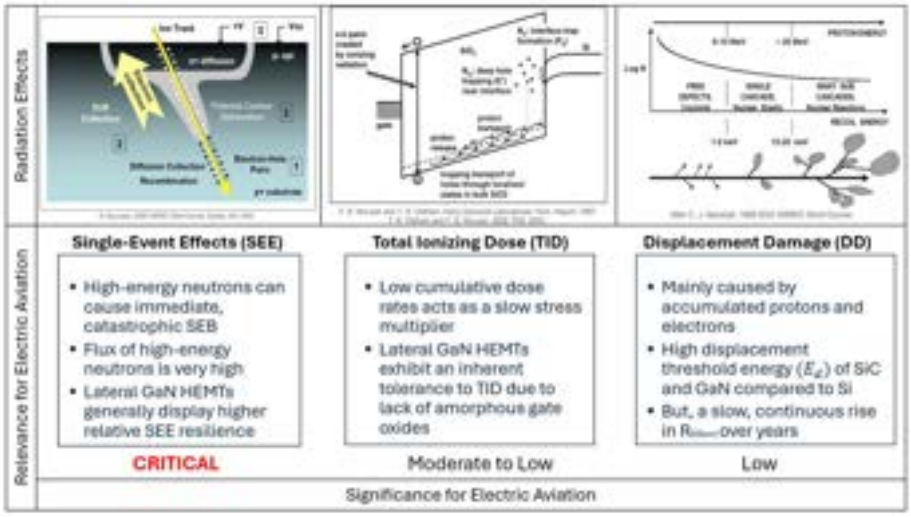


Figure 1. *Types of radiation effects, and their corresponding relevance and significance for electric aviation.*

3.Conclusions

The review of experimental data confirms that over a 30-years or more operational lifespan, cumulative TID and DD in SiC and GaN power devices remain well below the thresholds for significant parametric degradation. In stark contrast, the probability of neutron-induced SEB at aviation altitudes is found to be several orders of magnitude higher than acceptable safety limits when devices operate at rated voltages. This study concludes that the reliability of SiC-based electric propulsion systems is governed almost exclusively by stochastic SEE risks, specifically SEB and SEGR, rather than traditional wear-out mechanisms. This realization emphasizes the fundamental pivot in design philosophy in comparison to space application, that is moving away from ineffective shielding-based mitigation toward aggressive voltage derating and architectural redundancy. These findings provide a critical baseline for future

certification, demonstrating that while WBG devices are robust against cumulative dose, its vulnerability to atmospheric neutrons remains the primary hurdle for flight-critical WBG power electronics.

Heat exchanger for the hydrogen engine fuel system

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National Aerospace University "Kharkiv Aviation Institute", Ukraine

1. Introduction / Objectives

Hydrogen is a promising aviation fuel due to its high specific energy (120 MJ/kg, about three times higher than Jet at 43.2 MJ/kg), environmental compatibility, and resource renewability. However, its low temperature and density in the liquid state complicate onboard storage and fuel supply. Reliable hydrogen delivery to a gas turbine engine across the full operating range requires a Heat Recovery System.

Because of the high heat fluxes needed for hydrogen heating, combustion products are used as the primary heat source, typically extracted in the exhaust nozzle region. Systems with an intermediate coolant are complex and heavy, making direct heating a more compact alternative. However, this approach introduces a risk of heat exchanger surface icing under certain conditions, which can significantly affect heat transfer.

This study aims to analyze the icing effect using a thermohydraulic model of a heat exchanger, taking into account condensed-phase deposition on cold surfaces.

2. Methodology

For a direct hydrogen heating scheme (Fig. 1), the coupled heat and mass transfer processes during the formation of condensed phases (solid and liquid) are considered.

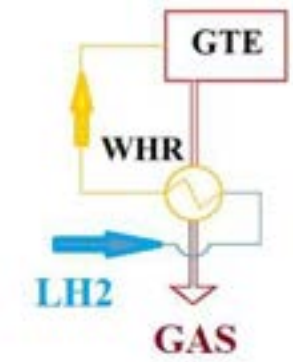


Figure 1. *Heat Recovery System with direct hydrogen heating: WHR – heat exchequer; GTE – gas turbine engine*

The analysis focuses on conditions under which a multicomponent solid layer and a liquid film simultaneously form on the wall, as shown in . The structure and composition of the ice layer may vary significantly across its thickness due to differences in the thermophysical properties of the diffusing components. Desublimation of a given component is completed when the

interfacial temperature reaches its melting point. Subsequently, components with higher triple-point temperatures crystallize, while others form a liquid film.
The interfacial temperature in contact with the gas mixture flow is determined from the heat balance equation, which states that the algebraic sum of heat fluxes to the interfacial surface is equal to the heat flux consumed by the phase transition. Heat flux is transferred to this boundary by radiation and convection, as well as by the phase change heat associated with the mass flow rate of the diffusing components. As the interfacial temperature increases, the diffusion flux of each component decreases. The diffusion flux ceases when the vapor density of the diffusing component in the bulk flow becomes equal to that at the interfacial surface.
It is important to note that no experimental data corresponding to these study conditions were found in the literature. In this regard, the model was verified by comparing the calculated results with experimental data obtained during testing of a hydrogen heat exchanger within the Tu-155 Program.

3. Results / Conclusions

The developed WHR thermal calculation method was extended by incorporating a model of the icing process. This enhancement made it possible, under steady-state conditions, to determine the ice layer thickness in each section of the heat exchanger tube, as well as the heat flux, while accounting for diffusion processes in regions of desublimation (ice formation) and water vapor condensation.
Using the developed model, the influence of key parameters on the icing process was investigated. These parameters include the heat exchanger tube diameter, hydrogen temperature, pressure and mass flow rate, as well as the temperature, composition, and pressure of the adjacent hot flow.
The results show that the increase in heat flux associated with diffusion processes has a more pronounced positive effect on heat transfer than the negative impact caused by the growth of thermal resistance due to ice layer formation. Consequently, under the considered operating conditions, icing does not necessarily degrade overall heat exchanger performance and may, in certain regimes, enhance heat transfer.

Acknowledgment: The research leading to these results has been performed in the frame of the "HYdrogen DEmonstrator for Aviation (HYDEA)" project. The project is supported by the Clean Aviation Joint Undertaking and its members in the framework of Grant Agreement n° 101102019 - HYDEA.

Cryogenic powertrains as key enabler for fully electric hydrogen fuel cell powered aircraft

Christian Bentheimer, Florian Bayer, Dr. Markus Meindl, Dr. Bernd Eckardt
Fraunhofer IISB, Germany

1. Introduction / Objectives

In support of the European Union's ambition to achieve climate-neutral aviation by 2050, hydrogen-powered aircraft (HPA) equipped with fuel-cell-based electric propulsion systems are emerging as a promising solution for zero-emission flight. However, achieving the required efficiency, power density, and scalability for large aircraft requires major advances in

electrical propulsion technologies. The availability of liquid hydrogen at cryogenic temperatures offers a unique opportunity to use hydrogen not only as a fuel, but also as an integrated cooling medium for the propulsion system. Cryogenic cooling can significantly improve the efficiency and power density of superconducting motors and power electronics while reducing system weight and thermal management requirements. Although recent projects have demonstrated the potential of cryogenic electric propulsion, challenges related to reliability, integration, and technology maturity remain. This study highlights cryogenic powertrains as a key enabling technology for future fully electric hydrogen fuel cell powered aircraft.

2. Methodology

Substantial government investment (such as H2GEAR , H2FlyGHT) and private ventures (such as ASCEND , CRYOPROP) have advanced cryogenic aircraft propulsion systems and have shown their potential. The current Clean Aviation Call 4 for Proposals, featuring specialized Fast Track Activity (FTA) calls, addresses the development of cryogenic powertrains with the FTA-05 (“Cryo-cooled power electronics“) and FTA-06 (“Superconducting motor windings“) calls. Fraunhofer IISB is the consortium leader of the proposed FTA-05 project ARCTIC and is part of the FTA-06 sister project ANTARCTIC. The Timeline of the FTA-05 and FTA-06 projects and connection to other Clean Aviation projects is shown in Figure 24. This study will present the planned work for both projects and show how they will contribute to the development of future fully electric hydrogen fuel cell powered aircraft.

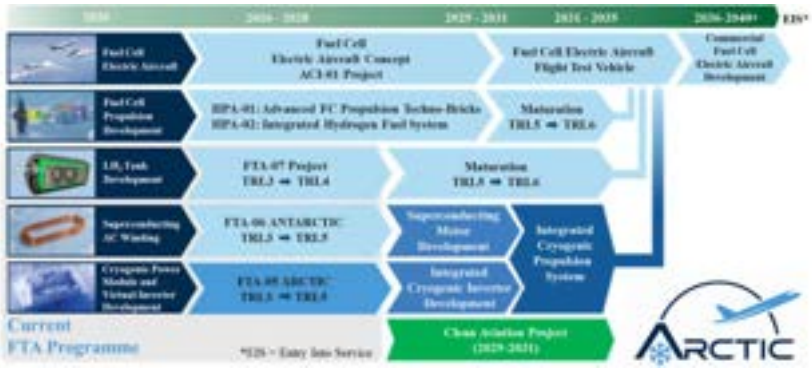


Figure 24. Timeline of FTA-05 and FTA-06 projects and connection to other Clean Aviation projects

In past projects for the development of cryogenic power electronics systems, off-the-shelf gallium nitride (GaN) semiconductor devices were utilised, which demonstrated increased efficiency when operated at cryogenic temperatures. However, challenges related to device packaging and reliability under cryogenic conditions and thermal cycling remain key limitations for long-term operation in such environments. The proposed ARCTIC (Advanced Reliable Cryogenic power module Tested for aircraft Inverter Circuit) project addresses these challenges. The main goal is to develop, test, and mature a cryogenic GaN power module to TRL5, meeting the performance targets to enable 2 MW cryogenic motor-control units for fully electric hydrogen fuel cell powered aircraft.

Superconductivity serves as an interesting solution to gain efficiency and power density advantages. The ANTARCTIC (Advanced supercoNducTing AC motoR Coils Thermallsed with Ceramics) project will advance the maturity of alternating current stator windings to TRL 5 through an integrated methodology. The main project goals are to successfully demonstrate an HTS coil integrated with a vibration-resilient ceramic cold plate, generate an unified AC

loss validation roadmap, and perform environmental and reliability testing by using cryogenic shakers and thermal cycling benches.

3. Results / Conclusions

Cryogenic powertrains represent a key enabling technology for future fully electric hydrogen fuel cell powered aircraft by significantly improving power density, efficiency, and system integration. The ARCTIC and ANTARCTIC projects address critical technological challenges in cryogenic power electronics and superconducting motor technologies, targeting TRL5 maturity for aviation applications. ARCTIC focuses on the development of reliable cryogenic GaN power modules capable of supporting multi-megawatt motor-control units, while ANTARCTIC advances superconducting AC stator windings with integrated cryogenic cooling and enhanced environmental robustness. Together, these projects contribute to overcoming current limitations related to thermal management, reliability, and scalability of cryogenic propulsion systems. Their combined outcomes are expected to support the realization of lighter, more efficient, and climate-neutral aircraft propulsion architectures, strengthening Europe's position in sustainable aviation technologies and accelerating the transition toward zero-emission aviation.

Advancing Cryogenic Cooling And Electrical Distribution Systems For Future Hydrogen-Powered Aviation

Daniel Kierbel [1], Reda Abdouh [2], Dominika Chamoro [3], Ikram Mataich [1], Arne te Nijenhuis [4], Marcel Schoonmade [3], Frank Wokke [3],René Alderliesten [5], Marc Dhalle [6], Gerhard Knol [7], Francesco Dioguardi [8], Frank van Duin [9], Max Van Vliet [3], Tim Hope[3], Ben Eastment [3], Matteo Tassisto [2], Emelie Nilsson [2] ,Jeremie Monin-Baroille [2], Jan-Willem van Zwieten [1]

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1. Introduction / Objectives

Decarbonizing aviation is one of the most significant challenges of the 21st century. As the industry moves toward hydrogen-powered flight, the maturation of cryogenic technologies becomes a critical enabler. Liquid hydrogen (LH2), stored at approximately 20K (-253°C), offers high energy density but introduces significant thermal and structural challenges. However, this low temperature also presents an opportunity: using the LH2 not only as a fuel but also as a coolant. This approach will enable high-efficiency electrical technology such as superconductivity and hyperconductivity.

Funded by the Dutch **"Luchtvaart in Transitie" (LiT)** program, the objective of the **ICEFlight** project is to develop specialized cryogenic cooling and electrical distribution systems leveraging a consortium of Dutch industries and knowledge institutions. The project aims to enhance powertrain performance and connect Dutch innovation with Airbus's broader

demonstration roadmaps, including the CRYOPROP demonstrator, and GKN's H2FLYGHT initiative.

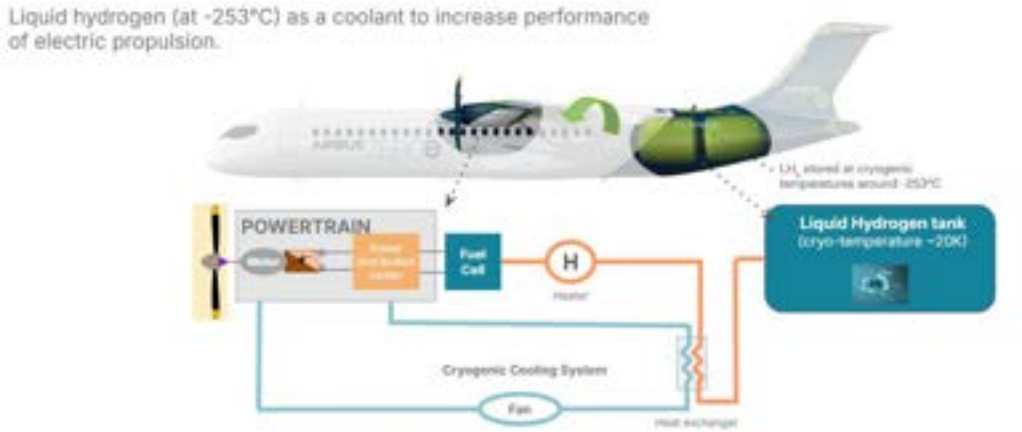


Figure 1: *general set-up of the ICEFLIGHT cryogenic electric propulsion concept*

2. Methodology

To transition cryogenic propulsion from conceptual design to airworthiness, ICEFlight implements a Verification & Validation (V&V) methodology structured around the three main pillars of the project's scope.

First, the maturation of cryo-technologies leveraging Dutch industry partners such as Cryoworld, Futura Composites, and Stirling Cryogenics, led by GKN Fokker, focuses on the development of specialized electrical distribution and cryogenic cooling systems, directly contributing to the development and advancement of Dutch industrial excellence.

Second, led by the Royal NLR, the consortium designs and operates world-class liquid cryogenic and hydrogen-based test facilities in Netherlands to validate these physical components under flight-representative conditions. Key installations include the cryoshaker mechanical testing bench, which validates the structural integrity of cryogenic components under relevant vibration at cryogenic temperatures, and the thermal and pressure cycling benches, which subject components to high-rate thermal gradients from ambient down to 20K to analyze fatigue and leak tightness. Furthermore, flight attitude and bending benches evaluate phase orientation under dynamic flight profiles using linear actuators and verify the physical limits of flexible cryogenic piping, culminating in full platform integration of the complete system on the experimental LH2 platform.

Third, to prove technology maturity and satisfy critical reliability objectives, ICEFlight utilizes high-fidelity, accelerated testing methods. This includes deploying agile de-risking test setups, such as a temporarily submerged liquid or gaseous nitrogen cryo-chamber, to bypass initial testing facility design bottlenecks and fast-track structural characterization. Concurrently, a partnership with the University of Twente (UT) enables simultaneous electrical-cryogenic characterization, running electrical performance measurements and vacuum-thermal cycles to guarantee zero performance degradation under operating stresses. In addition, the Delft University of Technology (TU Delft) aims to test and understand the fatigue and damage tolerances of materials in ambient and cryogenic environments, with the goal of establishing a state-of-the-art modeling methodology to accelerate the design process of components operating in harsh aircraft environments.

3. Results / Conclusions

The ICEFlight project (2025–2030) is currently focusing on the active design and technological development of its core cryogenic and electrical components. By the end of 2025, the consortium consolidated key foundational learnings in advanced vacuum management and preliminary component reliability. In 2026, the primary objective is the commissioning of the most testing infrastructures, specifically the cryoshaker vibration bench, pressure & thermal cycling benches, and the liquid hydrogen platform. Successfully activating these benches by the end of 2026 will allow the first campaigns of preliminary reliability testing on physical components under representative operational profiles. Ultimately, these phased achievements demonstrate how this distributed research ecosystem successfully matures technologies for commercial hydrogen aviation, establishing a specialized cryogenic "hotspot" in Netherlands with high spin-out potential for industrial, medical, and scientific applications.

ICEFlight: An exploratory study into LH2/GHe heat exchangers for a cryogenic-electric network

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1. Introduction / Objectives

To proceed maturation of cryogenic-electric powertrains for aviation, the Luchtvaart in Transitie-funded ICEFlight program is developing new cryogenic technologies for a cryogenic-electric network. In this endeavor, specific attention is given to elevate the technology readiness of super- and hyperconducting powertrain equipment cooled by a cryogenic cooling system, which uses liquid hydrogen as both a fuel and cold source. One of the considered equipment is a liquid hydrogen (LH2) to gaseous helium (GHe) heat exchanger, which is unprecedented, and has received little attention in earlier feasibility studies. Here, a working fluid trade-off will be performed, and a preferred LH2/GHe HEx will be selected.

2. Methodology

A leap in mass reduction and increased efficiency can be achieved, by operating the cryogenic-electrical equipment in a 30 K to 70 K temperature window. This temperature requirement amplifies the need for new cooling methodologies, i.e. the introduction of a cryogenic cooling loop. This cryogenic heat transfer system will enable the distribution of electronics waste heat to the cold source, the LH2 fuel flow, requiring a cryogenic intermediate fluid to provide the cooling distribution. Here, a trade-off is shown between potential working fluids in the stated cryogenic temperature range: gaseous Helium, two-phase Neon, and two-phase Hydrogen. This comprehensive trade-off focuses on component mass, required volume, thermal efficiency, and other parameters. In the separate component analyses, particular attention is given to the critical heat exchanger between the LH2 fuel flow and the cryogenic working fluid, which has to operate in a tight window with regards to thermal requirements. Moreover, the phase transition of hydrogen in the heat exchanger introduces additional complexity. For the heat exchanger, various types are explored. After an initial trade-off, a double-pipe heat exchanger, plate-fin heat exchanger, and printed circuit heat exchanger are selected for further analysis.

3. Results / Conclusions

An exploratory study is performed, considering various type of heat exchanger. Results on HEx characteristics have been generated. The most promising heat exchanger after a detailed trade-off is a printed circuit heat exchanger.
Additionally, the trade-off between fluids results in GHe as a clear preferred choice. Although Hydrogen as a cooling fluid has some favorable thermodynamic behavior, this benefit does not outweigh the benefit of GHe as a inert medium to cool the cryogenic electronics.
Based on the study, a recommendation is generated to focus on (1) printed circuit heat exchanger as highly efficient heat exchanger for LH2/GHe heat exchange, and (2) consider GHe as the primary cooling fluid, but consider the safety aspects of Hydrogen in more detail.

Validation of a Virtual Tool for Thermal Runaway Propagation in 21700 Format Lithium-Ion Battery Modules

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1. Introduction / Objectives

Modern CS-25 transport aircraft represent a subset of the potential aircraft that are candidates for increased electrification. These aircraft may use lithium-ion battery systems both for propulsion and non-propulsion-related applications. Whereas the service life of aircraft is typically 20 years or more, lithium-ion technology is subject to rapid advancement and still has a shorter expected service life. This mismatch makes battery replacement during service inevitable and introduces challenges related to long-term availability, consistency, and most likely re-certification. To address the latter, this paper presents a virtual-tool workflow based on a verified thermal runaway simulation model developed in the CONCERTO project. The approach allows early identification of critical design aspects, reducing the number of physical tests and improving the efficiency of the certification process. Regulatory guidance (e.g., EASA and FAA joint white paper “Thermal runaway for propulsion battery”) limits the use of simulation to identify critical test scenarios. Full-scale physical testing remains mandatory for thermal runaway propagation and containment verification. The virtual tool workflow therefore complements, rather than replaces, experimental validation.

2. Methodology

The workflow presented evaluates thermal runaway propagation in lithium-ion battery systems. A key challenge in directly verifying TR simulations with real cells is the strong scatter in TR behavior and the limited knowledge of the actual energy release and power profile during the TR experiment. Agreement between simulation and experiment can usually only be demonstrated statistically and requires many TR tests.
To circumvent this, an electrical power controlled, physical TR simulator is presented, allowing defined energy, power and pulse profiles. The simulator defines the experimental boundary conditions and yields reproducible measurement data that can be used to assess the thermal design and to compare with numerical models. Depending on the objective, the TR simulator is operated with representative average energy inputs or conservative worst-case assumptions. The latter enables the module’s thermal design limits to be explored and experimentally characterized.
The TR simulator presented in this paper has the geometric form factor of a 21700 cell and is

modelled as a homogeneous cylindrical heat source with equivalent mass, heat capacity and thermal conductivity. The effective thermal properties and heat transfer to the environment are derived from generic characterization tests with cooling curves. Defined power pulses are used for experimental evaluation of FEM/CFD modeling results.

The 21700 TR simulator is integrated into a scaled-down 4S3P mini-module. The mini-module is derived from a 14S3P, 21700-based aircraft battery design with a nominal voltage of 60 V. Deep-discharged 21700 cells act as thermal dummies inside the 4S3P configuration, with the central cell replaced by the TR simulator. The mini-module is mounted inside a metal housing and immersion-cooled with a dielectric fluid. Thermocouples are used to record the temperatures at the simulator, in the surrounding fluid and at neighboring cells.



***Figure 1**: Set up mini-module*

For the investigations presented in this paper, a single TR event in a high performance 21700 cell with a released energy of approximately 30 kJ is assumed. Experimentally this is achieved by a 15 kW power pulse lasting 2 seconds. The analysis of the measured transient temperature profiles serves to assess the thermal robustness of the mini-module. It forms a basis for future numerical studies as well as a subsequent comparison with data from real cell TR tests.

3. Results / Conclusions

In the 21700 mini-module tests, the internal simulator temperature increases from about 20 °C to 820 °C within approximately 4 s. This corresponds to a temperature rise rate of ~200 °C/s for an energy input of 30 kJ. The predefined validation criteria for the 21700 use case (≥175 °C/s, 30 kJ, ≥700 °C) are therefore met.

Thermal Management

Chaired by:
Mr. Guillaume Bourely (Honeywell, Czech Republic) & Prof. Michael Weigand (TU Wien, Austria)

A Mission-Level Simulation Framework for Integrated Thermal Management of Hybrid-Electric Aircraft Power Systems

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1. Introduction / Objectives

Hybrid-electric aircraft introduce strongly coupled thermal loads among cabin conditioning, electric powertrain cooling, and aircraft-level heat sources and sinks . In early design phases, these couplings must be assessed over complete missions rather than at static operating points, because transient thermal constraints can drive architecture feasibility, energy demand, and certification-relevant operating margins. The novelty of this work lies in the transient, mission-level co-simulation of the environmental control system (ECS) and power-related thermal loads, such as those from batteries and fuel cells, within a unified Modelica-based aircraft thermal management framework . By linking parameter studies to key performance indicator (KPI)-based assessments of architecture feasibility and thermal margins across complete flight profiles, the framework enables early identification of key subsystem interactions that would remain unresolved in static operating-point analyses. It therefore serves as a virtual test bench for maturing and evaluating thermal management concepts toward higher technology readiness levels (TRLs).

2. Methodology

The proposed framework combines two formerly separate digital-twin models into an integrated aircraft thermal management system model . The model architecture is designed to support scalable subsystem coupling through structured bus systems and signal-based interfaces. This approach enables the consistent exchange of thermal states, heat flows, control signals, and mission-dependent boundary conditions between the ECS and the power system. Figure 1 shows the resulting integration into a single Modelica framework.
The mission profile block covers complete dynamic flight missions, including ground operation, climb, cruise, descent, and landing. Within these simulations, subsystem temperatures, available thermal margins, energy flows, and control responses are evaluated as time-resolved quantities. The framework is therefore suited not only to component-level thermal analysis, but also to aircraft-level assessment of architectural design choices over the full mission. Dedicated mission-level KPIs include total mission energy, certification-relevant temperatures, such as those of the cabin and power electronics, and drag. Constraint violations are quantified, enabling the identification of critical operating points for each subsystem.
Architectural variation studies are performed for representative hybrid-aircraft use cases. These include parameters such as cabin air recirculation under cold-day conditions, battery power, and sizing assumptions. By varying these assumptions within the same integrated

framework, local component responses can be linked directly to aircraft-level performance indicators and mission feasibility. This capability enables the digital twin, developed within the TheMa4HERA project, to function as a virtual test bench. For example, detailed in-flight cabin temperature distributions are used to calculate temperature gradients and assess whether the environmental control system can meet certification requirements. These capabilities provide essential input for future aircraft design decisions.

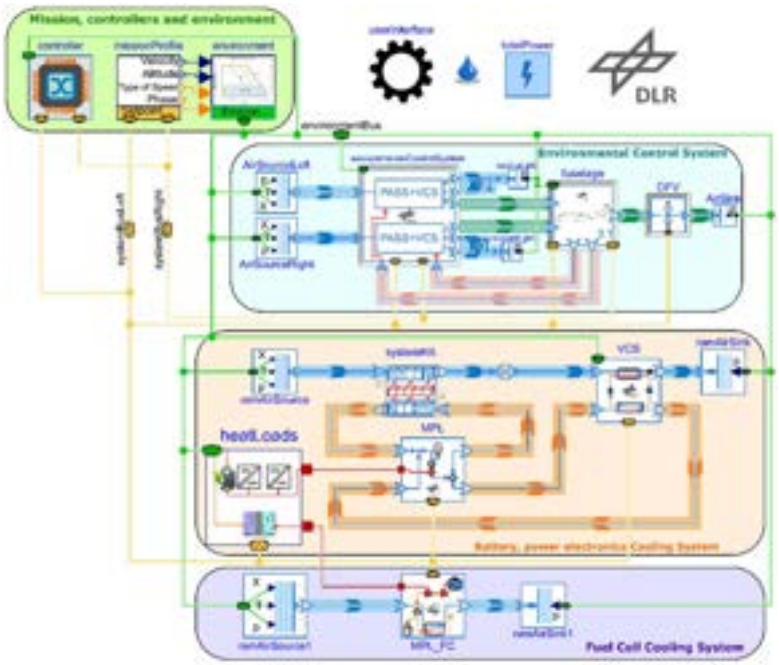


Figure 1. *Integrated model framework of ECS, Power electronics and FC System*

3. Results / Conclusions

The integrated framework enables mission-resolved evaluation of hybrid-aircraft thermal management architectures and reveals critical interactions that would be difficult to identify using isolated subsystem models. The KPI-based assessment links local thermal behaviour to aircraft-level performance, allowing design options to be compared in terms of comfort, thermal constraint compliance, and mission energy or fuel demand. Exemplary sensitivity studies show that changes in cabin recirculation, battery sizing, and coolant properties can affect not only component temperatures, but also the usable thermal capacity and operational robustness of the complete aircraft system. The framework therefore provides a structured basis for early design-space exploration, architecture comparison, and identification of robust thermal management concepts for future hybrid-electric aircraft. When validated TRL 5 models are integrated into this framework, it can function as a virtual test bench for TRL 5 system assessment.

System Modelling and Simulation of an Integrated Thrust Recovery System with an Outflow Valve for Next Generation Hybrid Electric Regional Aircraft

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1. Introduction / Objectives

The Clean Aviation TheMa4HERA (Thermal Management for Hybrid Electric Regional Aircraft) project aims to develop advanced thermal management architectures and technologies for next-generation hybrid-electric regional aircraft, contributing to the European Union's greenhouse gas emission reduction goals.
Thermal management systems are among the key onboard systems with substantial energy-saving potential, enabled by the development of more efficient technologies. Within these systems, the Cabin Pressure Control System (CPCS) plays an important role, and the outflow valve (OFV), as a key CPCS component, offers significant opportunities for improving efficiency through thrust recovery capabilities. This work focuses on the development and verification of a Modelica-based subsystem model of a high-efficiency outflow valve (OFV) with control system to evaluate thrust recovery performance while ensuring proper performance of cabin pressure control over the mission profile. The validated model also provides the basis for integration into a full aircraft thermal management digital twin for system-level simulation and assessment.

2. Methodology

A Modelica-based subsystem model of the Cabin Pressure Control System (CPCS) for a regional aircraft is developed with the Dynamic modelling Laboratory (Dymola). The model includes the cabin, recirculation fan, outflow valve with thrust recovery, and the associated control system. The key physical characteristics of each component are represented through component-level modelling and integrated into a unified CPCS subsystem model, as illustrated in ***Figure*** .

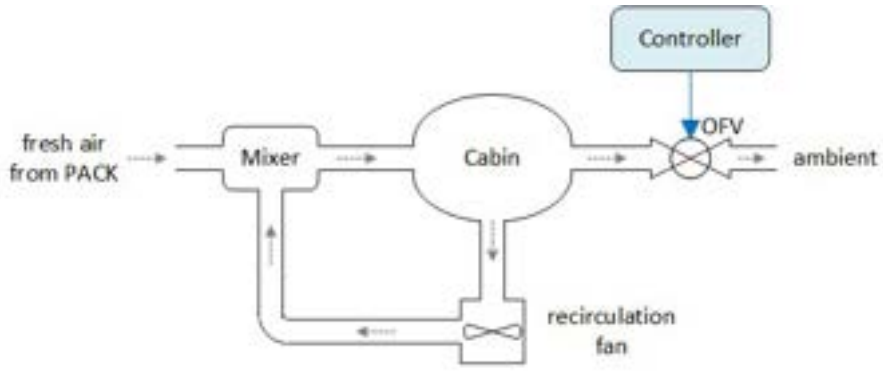


Figure 57. *Schematic of the Modelica-based subsystem model of the Cabin Pressure Control System*

The subsystem model is applied to evaluate key performance indicators, including cabin pressure, air mass flow, and thrust. Thrust recovery performance is validated against CFD simulation data under representative operating conditions, demonstrating acceptable

average deviations between the prediction and reference results. Further validation using laboratory test data is planned for Q3 2026.
The validated model supports whole mission-profile simulations and is integrated into a comprehensive digital twin of the aircraft thermal management system, enabling aircraft-level simulation and system-wide performance assessment.

3. Results / Conclusions
Thrust recovery predictions from the Modelica subsystem model show deviations within 10% compared to high-fidelity CFD results across representative operating conditions. The validated subsystem demonstrates effective thrust recovery while ensuring compliant cabin pressure control throughout the mission profile. Furthermore, the model provides straightforward integration integrable into a full aircraft thermal management digital twin, enabling efficient system-level simulation and assessment.

Acknowledgement: This work is supported in part by European Union with Clean Aviation Project TheMa4HERA (Thermal Management for Hybrid Electric Regional Aircraft) under Grant 101102008.

Development and Assessment of Thermal Management System for Hybrid-Electric Propulsion Applications within the ETHAN1 Project

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1.Introduction / Objectives
The increasing electrification of aircraft propulsion systems introduces significant challenges for thermal management, particularly due to the high flux low grade heat loads generated by electrical machines, power electronics, batteries, and auxiliary systems. The strict operating temperature requirements, low grade heat generation together with the minimum weight, drag and power requirements make thermal management system (TMS) design very complex and impacts the aircraft performance . It is obvious that the TMS may completely offset the benefits of electric propulsion if not properly designed and operated. Novel heat exchangers and cooling concepts are crucial for the optimal design of TMS overcoming the challenges associated with electric propulsion systems . Within the ETHAN1 project at the chair of aeroengine design, simulation tools and experimental facility were developed to support the design, testing, and assessment of novel heat exchanger concepts and overall TMS. The work presented as part of this study can be broadly classified in three areas: theoretical modelling of TMS and heat exchangers, TMS test bench development, and thermo-mechanical assessment of heat exchanger architectures with Periodic Open-Cellular Structures (POCS).

2. Methodology
TMS modelling and heat exchanger sizing tools were established for hybrid-electric propulsion systems. These models support preliminary assessments of heat rejection requirements, thermal resistance, pressure-loss constraints and geometric sizing of compact heat exchanger designs. These simulation models also enable early-stage system-level performance assessment and provides design guidance before detailed numerical or experimental investigations. In addition, a modular TMS test bench was developed and

commissioned to enable experimental characterization of novel heat exchanger concepts, including additively manufactured POCS. The test bench provides a controlled environment for evaluating pressure drop, heat transfer performance, flow behavior, and operational feasibility under representative boundary conditions. This experimental capability forms the basis for validating novel lightweight heat exchanger concepts intended for aviation thermal management systems. Finally, the thermo-mechanical behavior of POCS-integrated heat exchanger structures was investigated using theoretical and experimental methods. The analysis considered geometry-dependent thermo-hydraulic performance, mechanical response, and potential integration into heat exchanger cores. These investigations provide insights into understanding whether lightweight cellular structures can satisfy not only thermal performance requirements but also mechanical durability and operational safety constraints.

3. Results / Conclusions

Overall, the ETHAN1 project established an integrated foundation for the development of advanced thermal management systems for hybrid-electric propulsion in aviation. By combining test bench capability, heat exchanger sizing, and thermo-mechanical assessment of architected cellular structures, the work supports the transition from conceptual thermal management design toward experimentally validated and mechanically robust heat exchanger solutions for future electrified aircraft propulsion systems. Figure 1 presents as an example the pressure drop characteristics of Lidinoid structure integrated on the air side of heat exchanger.

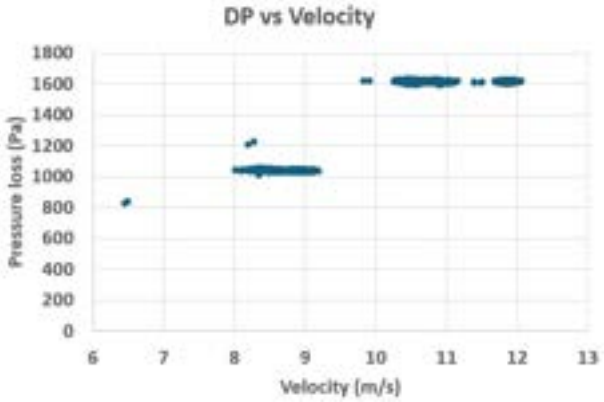


Figure 1. *Pressure drop characteristics of Lidinoid structure*

Influence of Ram Air Channel Cooling Capability and Associated Drag on Fuel Cell Operation and Aircraft Mission Performance

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1. Introduction

Future hybrid electric aircraft concepts have system limitations and operational constraints which can lead to major power constraints during flight mission. To verify the feasibility of new hybrid propulsion concepts, a dynamic simulation of an overall aircraft system model is developed.

The objective in this study is to investigate the cooling power limitations of the fuel cell cooling system, its associated drag and its influence on fuel cell operation and mission trajectory, while having all relevant component limitations, dependencies and controls included. This allows the identification of critical operation points during the mission and the evaluation of the most relevant properties such as ambient temperature or ram air channel design. Furthermore, the integration of a fan is analyzed to compensate the lack of cooling power in critical flight phases.

2. Methodology

An overall aircraft system model is developed in Modelica, including batteries, fuel cell (FC), electric drives, propellers and finally the aircraft and ram-air channel. To get a realistic system response, all relevant dynamic behaviours and system or component limitations are included in the models. The relevant controls are implemented to connect the individual systems and to have their interactions included.

A key feature of the model is the use of physically realistic inputs and outputs. For example, the inputs of the aircraft model are thrust forces, drag forces and pitch angle controlled by a pilot control to achieve a certain flight mission instead of fixed altitude and speed profile input. Using this modeling approach, the influence of certain system behaviours, limitations or control strategies on the flight envelope can be investigated.

To implement the fuel cell temperature control and its associated drag, a ram air channel model is developed including a diffuser and a nozzle with a certain efficiency and a heat exchanger. The pressure drop and heat transfer coefficient of the liquid to air heat exchanger is calculated based on the colburn and fanning friction factor correlations . With an inlet and outlet area control, the cooling air massflow and the inlet capture ratio can be controlled individually to minimize the drag of the ram air channel.

Without a fan, the available cooling power is restricted by several factors. The fuel cell temperature control not only includes the ram-air channel control, but also has the possibility to limit the fuel cell power to avoid temperature overshoots and ensure a safe fuel cell operation over the entire mission. With this control approach, the influence of the resulting fuel cell operation on other components and the flight envelope for example at take off can be investigated. The simulation results presented in this paper are based on the EU Clean Aviation project AMBER. In figure 1, the hybrid electric propulsion architecture following the AMBER aircraft concept is shown.

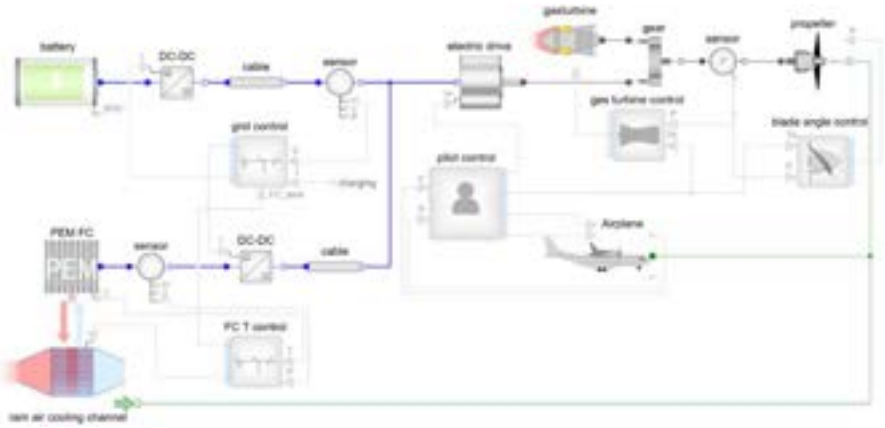


Figure 1. *Dynamic simulation model of a hybrid electric powertrain architecture.*

3. Results / Conclusions

The simulation results show that the most severe fuel cell power limitations occur during flight phases with low airspeed and high ambient temperatures, such as takeoff and go-around. Apart from ambient ground temperature which has a significant influence, also takeoff altitude, fuel cell operating temperature, and ram-air channel design significantly affect the available cooling power.

Concerning the ram-air channel design, it was found that the heat exchanger and diffuser have the greatest impact on cooling power and aerodynamic drag. While the heat exchanger design has a direct influence on the cooling power and therefore fuel cell operation, both the diffuser efficiency and heat exchanger design have the strongest influence on the resulting drag, leading to an indirect limitation of fuel cell power, as a significant part of the propulsion power is used just to compensate the drag of ram-air channel.

Acknowledgement: The project is supported by the Clean Aviation Joint Undertaking and its members in the framework of Grant Agreement n° 101102020 - AMBER. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

HyPoTrade: Modelling and Simulation of a Two-Phase Mechanically Pumped Loop for Fuel Cell Waste Heat Recovery

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1. Introduction / Objectives

One of the key challenges in the development of hydrogen fuel cell powered aircraft is the significant amount of waste heat generated. The produced heat can be partially recovered by conditioning liquid hydrogen to a desired temperature. A two-phase mechanically pumped loop (2Φ-MPL) can be used to efficiently transfer heat from the fuel cell towards a liquid hydrogen flow, such as is done in the HyPoTrade project.

2. Methodology

This paper focuses on the modelling and simulation of a 2Φ-MPL, using the HyPoTrade two-phase transfer loop as a case study and investigating the possibility of modelling a 2Φ-MPL using an acausal approach. Two models have been developed, one model using OpenModelica based on DLR's ThermoFluid Stream library (1) and one model using MathWorks Simscape. Furthermore, a MATLAB tool has been developed, enabling a quick conversion from NIST REFPROP fluids to OpenModelica, without the use of a wrapper. This enhances the performance of the model. The main goal is that the models can be used for conceptual design of two-phase heat transfer systems and be integrated within a digital twin. This paper addresses the capabilities of the models, aiming to quantify the performance and transient behaviour of the recovery system as seen in the HyPoTrade project. In this paper, the working of the models is detailly described and their capabilities and limitations

are listed, including the possibility of a Functional Mock-up Unit (FMU). Furthermore, the steady state performance is assessed by comparing conceptual design simulations with existing MATLAB models, providing insight in different modelling approaches for 2Φ-MPL. Subsequently, model simulations are compared with experimental data to visualise the transient performance and quality of the model.

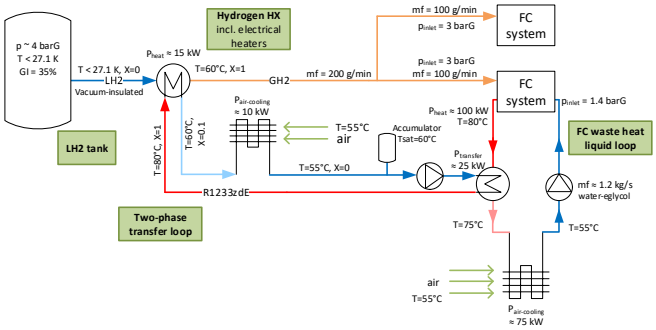


Figure 1. *System sketch for the HyPoTrade hydrogen conditioning system, with the FC waste heat liquid loop, interfacing with the Two-phase transfer loop. X denotes the refrigerant's vapour mass fraction.*



Figure 2. *OpenModelica schematic of a* 2Φ-MPL

3. Results / Conclusions

The differences between different modelling approaches are assessed and identified. This provides insight in the model capabilities and potential use for conceptual design of 2Φ-MPL. Furthermore, the transient behaviour is analysed by comparing with experimental data and the discrepancies are discussed. By showing the transient performance of the model, conclusions can be made regarding the implementation in a digital twin, either through an OpenModelica environment or via a FMU.

Development of PHM Concept for HERA Thermal Management System

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1. Introduction / Objectives

This work establishes a Prognostics and Health Monitoring (PHM) framework for the Thermal Management System (TMS) of next-generation Hybrid-Electric Regional Aircraft . The primary objective is the definition of health indicators (HIs) that support the prognostic capabilities of the TMS, thereby enabling early identification of the TMS degradation, preferably prior to actual malfunction or failure of the system and/or its components. By utilising these indicators to recognise early signs of degradation, the proposed framework aims to improve operational reliability and streamline maintenance planning.
A case study of the health indicator (HI) identification and validation for Vapour Cycle System (VCS) with focus on the VCS refrigerant charge level prediction will be presented.

2. Methodology

The project introduces a design methodology for Prognostics and Health Monitoring (PHM), executed in three sequential phases. First, components and failure modes with high potential for PHM were selected using a scoring system based on in-service experience; each mode was evaluated by a **Value Impact Assessment Level** (reliability and operability inputs) and a **Predictive Maintenance Assessment Level** (monitoring feasibility and performance). Second, existing fleet data, predictive concepts, and sensor architectures were analysed to develop **Health Indicators (HIs)** for monitoring and trending component degradation, including recommendations for additional sensors where necessary. Finally, a plan was established to validate the HIs using **Digital-Twin simulations**, **laboratory testing**, and **expert judgements**.
The methodology was tested on VCS. Major failure modes for the VCS components were identified and assessed with respect to the relevance for implementation of the PHM. A general set of HIs was developed to monitor and predict these failure modes. Finally, the HIs were validated using a data set generated by a VCS digital model. The model provided simulated data for the VCS operating under various ambient, operation and degradation conditions. The degradation conditions represented the VCS refrigerant leakage by simulation of the system operating with various levels of the refrigerant charge. Figure 1 shows results of the HI validation for VCS refrigerant charge level in the range from 60 % to 100 % of the nominal refrigerant c

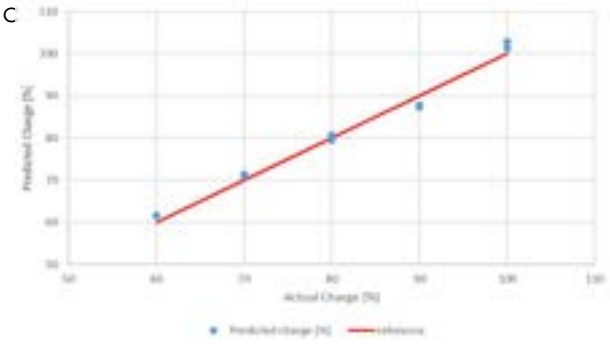


Figure 1. *Results of validation of the HI for VCS refrigerant charge level.*

3. Results / Conclusions

A predictive maintenance health monitoring concept for relevant TMS functions was developed during the early design phases of HERA aircraft. Its implementation will facilitate a transition to predictive maintenance, enhancing reliability and availability while optimising costs.

Ongoing efforts involve validating Health Indicators (HIs) for individual sub-systems and quantifying benefits related to Operational Impact (OI) and Direct Maintenance Costs (DMC).

A set of general HIs for the Vapour Cycle System (VCS) with focus on the VCS refrigerant charge level prediction was developed and validated using model simulated data. The HI was able to predict the actual system charge level with sufficiently high accuracy to be applicable for predictive maintenance. Further maturation and improvements of the HI are planned to enable its implementation in a real operational environment.

Reduced-Pressure Evaporation for Improved Thermal Management Performance of Fuel-Cell-Powered Aircraft

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1. Introduction / Objectives

Thermal management is a key limiting factor for low-temperature fuel-cell-powered aircraft, as large amounts of waste heat must be rejected at relatively low temperatures . Conventional ram-air cooling systems must be sized for hot-day take-off, resulting in substantial oversizing and cruise drag penalties of up to 20–25%.

Previous work has shown that water-evaporation-supported cooling can alleviate this constraint by providing a high-energy-density, transient heat sink . However, practical implementation concepts and their aircraft-level benefits remain insufficiently quantified.

This study focuses on reduced-pressure evaporation as a high-performance implementation of evaporative cooling. The objective is to assess its thermodynamic potential and to compare it at aircraft level against battery-supported cooling as an alternative for handling peak thermal loads during take-off. The work is conducted within the EU project TheMa4HERA.

2. Methodology

The study considers a hybrid thermal management architecture consisting of a conventional closed-loop fuel-cell cooling system and an auxiliary system used exclusively during peak load conditions (e.g. take-off), see Figure 1a. Two alternative solutions for this auxiliary function are analysed: (i) reduced-pressure evaporation system, and (ii) battery-supported cooling, where excess heat is indirectly managed by reducing fuel-cell load via supplemental electrical power.

The reduced-pressure evaporation system is modelled as an open-loop high-temperature heat pump using water (R718) as working fluid. Evaporation is induced by lowering the saturation pressure below ambient conditions, enabling phase change at fuel-cell-relevant temperatures (~80–105 °C). A thermodynamic model is developed including: (i) phase equilibrium and saturation properties, (ii) compressor work and resulting coefficient of performance (COP), and (iii) heat-transfer constraints between coolant loop and

evaporator.
The model captures the strong dependence of performance on evaporation temperature, which determines both compression ratio and achievable COP, see Figure 1b.
For the battery-supported case, a system-level model is used in which batteries provide additional electrical power during take-off, thereby reducing fuel-cell load and associated waste heat. Battery mass is determined based on required energy and power, considering representative specific energy and C-rate limits.
Both concepts are evaluated under consistent boundary conditions representative of hot-day take-off. The analysis is integrated into an aircraft-level framework , enabling comparison in terms of: (i) additional system mass (water vs. battery), (ii) power consumption (compressor vs. battery discharge), (iii) impact on ram-air system sizing, and (iv) resulting effects on aircraft drag and mission energy consumption.
Parametric studies are conducted with respect to fuel-cell operating temperature, take-off duration, and system design parameters to identify favourable operating regimes.

3. Results / Conclusions

The results show that reduced-pressure evaporation provides a highly effective transient heat sink with higher specific heat-rejection capacity than batteries. Due to the exploitation of latent heat, the required mass of consumable water is substantially lower than the equivalent battery mass for typical takeoff durations.
At fuel-cell temperatures above ~90 °C, reduced-pressure evaporation achieves high theoretical COP values at moderate compression ratios, see Figure 1b, limiting auxiliary power demand and avoiding the strong "snowball effect" associated with conventional heat-pump systems.
Compared to battery-supported cooling, the evaporation system enables greater reduction of peak thermal load on the ram-air system, allowing further downsizing and associated drag reduction.
Aircraft-level results indicate that reduced-pressure evaporation can outperform battery-supported solutions in terms of mass, efficiency, and integration potential, making it a promising approach for managing peak thermal loads in fuel-cell-powered aircraft.

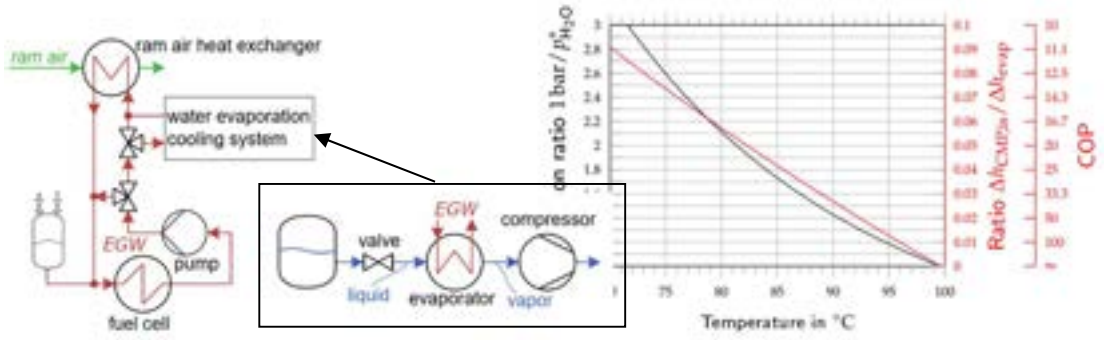


Figure 1. *(**a**) Schematic of reduced-pressure evaporation; colors denote fuel cell cooling loop (red, ethylene glycol water, EGW), water (blue, liquid and vapor); (**b**) evaporation performance: compression ratio (black, left y-axis) and theoretical coefficient of performance COP (red, right y-axis) depending on the evaporation temperature; $p^*_{H_2O}$ is the vapor pressure of water, Δh_{evap} is the enthalpy difference of evaporation, and $\Delta h_{CMP,is}$ is the compressor isentropic specific work.*

Integrated Modelica Modeling and Simulink Control Development of a Heat Exchanger System for Fuel Cell Propulsion

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1. Introduction / Objectives

The European Union's green transition aims to achieve climate neutrality by 2050, with an intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030 . The Clean Aviation HEROPS (Hydrogen-Electric Zero Emission Propulsion System) project aims to develop a climate-neutral fuel cell propulsion system for regional aircraft . A key challenge within this system is thermal management, as fuel cells generate significant amounts of low-grade heat at the megawatt scale. To address this, a high-performance heat exchanger system is required to effectively dissipate heat while minimizing aerodynamic drag. This presentation covers the development of a Modelica-based heat exchanger system model and the methodology for designing an open loop control scheduling strategy to ensure high-efficient and intelligent operation of the system throughout mission profile.

2. Methodology

A detailed Modelica-based model of the heat exchanger system is developed, encompassing the air inlet, ducts, heat exchangers, variable flow device (VFD), and air outlet. Key physical behaviors of the components are captured through component-level modeling, which is then integrated into a complete heat exchanger system model . The main performance metrics include heat transfer, pressure drop, mass flow rate, drag, and thrust. The integrated system model is validated against CFD results across various operating conditions within a mission profile, achieving an acceptable average deviation for both heat transfer and pressure drop. The validated model provides a foundation for FMU-based integration with other subsystems to support the development of a complete fuel cell propulsion system. ***Figure*** illustrates the schematic of the heat exchanger system.

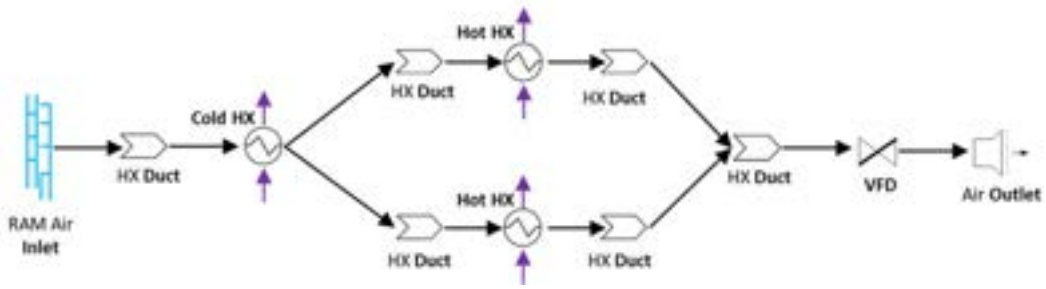


Figure 1 *Schematic of the heat exchanger system*

Building on the system modeling work, a model-based control approach is developed to adjust the variable flow device (VFD) relative opening angle at the air outlet of the system. This

allows the thermal profile of the heat exchanger system line connected to the fuel cell thermal management system to be regulated and accumulated heat to be dissipated continuously on command. Using the validated heat exchanger system (HXS) model, exported as an FMU for integration in Simulink, control-oriented models are developed under various operating conditions using system identification methods. Following model verification, an open-loop control law (illustrated in ***Figure***) is formulated based on measurable quantities at the HXS intake. Finally, the HXS control system is implemented and analyzed in Simulink to evaluate its performance and robustness under perturbed and steady-state conditions at different mission points. The results of the framework, which is based on a detailed Modelica-based heat exchanger system model, are very promising.

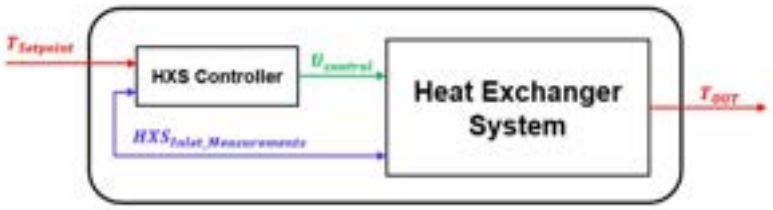


Figure2. *HXS Open-Loop Control Scheme*

3. Results / Conclusions

The integrated Modelica model of the heat exchanger system is validated against CFD simulation results under key operating conditions, with an average deviation of no more than 15%. The validated model also enables full-system simulations across the entire mission profile. The derived control-oriented models achieved a percentage match exceeding 70% with the FMU outputs of interest, according to which the control law parameters were computed. Implementing the open-loop control scheme on the FMU in Simulink resulted in acceptable reference tracking performance, with an average relative error of less than 12% at critical mission points.

Acknowledgment: This work is supported in part by European Union with Clean Aviation Project HEROPS (Hydrogen-Electric Zero Emission Propulsion System) under Grant 101140499.

Test results of a 150kW Direct Water Evaporation Demonstrator for Improved Fuel Cell Thermal Management in Aerospace Applications

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1. Introduction / Objectives

A major contributor to overall aircraft drag for next generation hybrid-electric and hydrogen fuel cell powered aircraft is cooling drag due to the high power heat rejection requirements at low temperatures (90-105°C). By dissipating thermal energy generated in the Fuel Cell (FC) through the evaporation of water during high power, low velocity and high ambient

temperature flight stages (e.g. take-off and initial climb stages), (ram) air heat dissipation requirements are reduced significantly or eliminated. Consequently, the ram air HX and associated ducting may be designed for later climb or cruise conditions, significantly reducing cooling drag. In this paper, test results are presented and discussed for a novel Direct Water Evaporation (DWE) demonstrator with a heat dissipation capacity of 150kW.

2. Methodology

The developed demonstrator has two operational modes: evaporation at ambient pressure (T_{evap}=100°C) hereinafter referred to as pump mode, and evaporation at sub-ambient pressure (T_{evap}< 100°C) hereinafter referred to as compressor mode.

In pump mode, water at approximately 20°C is pumped from a storage vessel to a Brazed Plate Heat Exchanger (BPHE). In the BPHE heat is supplied to the water, converting the liquid water to superheated steam. The superheated steam exiting the BPHE is then ejected to the environment.

In compressor mode, a centrifugal compressor drives the mass transfer from the water vessel to the environment. First, water exits the storage vessel at environmental pressure (~1 atm) and it is passed through a proportional valve that reduces the water pressure to a sub-ambient pressure, then it enters the BPHE in which superheated steam is generated, finally the superheated steam enters the compressor which compresses the steam back to ambient and ejects the steam to the environment. The proportional valve is controlled to set the compression ratio in the compressor and the saturation temperature in the BPHE. This reduction in saturation pressure and temperature is required since aerospace hydrogen fuel cell technology typically operate at a temperature of 90-100°C, which means that water cannot be evaporated at 1 atm. The pump mode could be applied in combination with a high temperature proton exchange membrane FC, which typically have an operating temperature of >120°C.

Heat is supplied to the BPHE utilizing a 200kW single-phase (1Φ) Mechanically Pumped Loop (MPL).

This MPL allows for control of the supplied thermal power, as well as the temperature at which the power is supplied.

3. Results / Conclusions

Test results will be provided for the pump mode as well as the compressor mode. The results of the pump mode will be provided at a constant saturation temperature with a thermal power of 150kW. Test results in compressor mode will be provided for several compression ratios which are constant over time. Furthermore results are presented in which the compression ratio is decreased over time, emulating dynamic take-off and climb conditions encountered during operation of a DWE system.

Impact of Puller Fan Integration on the Design and Off-Design Performance of a Hybrid-electric Fuel Cell Aircraft Thermal Management System

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1. Introduction / Objectives

Thermal management remains a major challenge for integrating fuel cells (FCs) into aircraft propulsion systems . Current architectures typically employ liquid cooling loops coupled with ram-air heat exchangers to reject waste heat during flight . To improve off-design operation and enable ground operations, several authors have studied adding a puller fan to the ram air duct . The fan is often modeled using simplified assumptions, such as constant efficiency and fixed pressure ratio, which neglect the strong coupling between the fan and the duct systems . As a result, despite the off-design performance improvements, the true mission-level impact of fan integration remains uncertain. Beyond the already established off-design advantages, the analysis focuses on how fan integration affects overall aircraft-level efficiency when the complete aircraft mission is considered, coupled with a more realistic modeling of the puller fan.

2. Methodology

The thermal management system (TMS) architecture considered comprises a ram-air channel with diffusor, a heat exchanger (HX) and a nozzle. The nozzle is assumed to have a variable geometry. The HX model is based on the methodology from . The fan modelling is based on a performance map taken from , which has similar size and pressure ratios as the ones expected for the design. For each flight point across the mission profile, the system resistance as a function of mass flow rate defines a distinct curve. Intersecting this curve with the fan performance map determines the fan operating point for each Mach number–altitude combination, from which the corresponding efficiency, rotational speed, and pressure ratio are obtained. Figure 1 illustrates the variation of the fan operating point with flight speed. At a constant volumetric flow ($\dot{Q}$), the system curve shifts downward with increasing speed, moving the operating point to lower pressure ratios (ΔP) and rpms. The fan power at each point is used to define the final FC deck, indicating the net FC power output at each flight point, along with the maximum FC load that the TMS can handle at each flight condition.

This study considers an 80-seat, twin-turboprop aircraft from the Clean Aviation HERA project . It features a parallel-hybrid electric propulsion system. Two wing-mounted gas turbines via electric motors support the fuselage-mounted FCs during the off-design phases. The TMS sizing routine is integrated inside an aircraft design workflow, where the input are the top-level aircraft requirements for the concept. The aircraft is iteratively sized based on the calculated FC decks that result from the TMS sizing routine. These are simulated along the mission profile to compute the gas turbine and FC power profiles, as well as the fuel consumed along the mission. The TMS is cruise-optimized to dissipate the full heat produced by the FC operating at full load. During off-design, the gas turbines supply the missing power.

3. Results / Conclusions

The fan mitigates the gas turbine's contribution during off-design conditions, expanding the

range of flight points where the TMS ensures to dissipate the full FC heat load. This allows for continuous FC operation and a reduction in kerosene consumption. The reduction in fuel burnt during off-design comes with penalties, mainly the mass of the added systems and the power to keep the fan running during the cruise phase (7% of the total FC power output). This leads to a reduction in the net FC power output and a subsequent increase in fuel burn, though this is partially offset by the drag reduction achieved through fan operation during cruise. The nozzle area of the duct plays a crucial role in the feasibility of the architecture. A variable area nozzle becomes indispensable due to the great variety of flight altitudes and Mach numbers at which the TMS operates. An adaptable outlet area, allows to tailor the system resistance curve to always intersect the fan map at the optimum point for minimum power requirements.

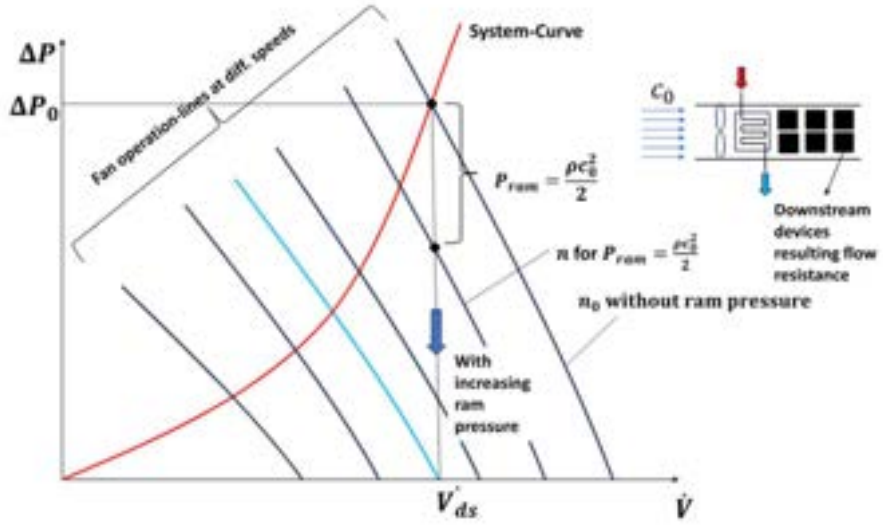


Figure 1. *Operating behavior of a fan. Response of fan speed against increasing ram pressure for a given mass flow*

Loss Mechanisms and Efficiency Limits in Fuel Cell Ram Air Cooling Channels: Diffusers, Heat Exchangers, and the Meredith Effect

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[2] OTH Regensburg, Germany

1. Introduction / Objectives

Thermal management represents a key integration challenge for hydrogen fuel cell aircraft due to the low operating temperature of proton-exchange membrane fuel cells, which necessitates high cooling air mass flow rates and leads to substantial aerodynamic penalties of up to 20–25% in ram-air-based systems.
This work investigates the fundamental aerodynamic and thermodynamic loss mechanisms in ram-air cooling channels from a first-principles perspective. Particular emphasis is placed on the interaction between pressure recovery, heat addition, and expansion, commonly

referred to as the Meredith effect.
The objective is to derive physically consistent efficiency limits and to identify optimal design conditions for diffuser geometry, heat exchanger performance, and flow matching. Furthermore, the study quantifies the degradation in system efficiency when deviating from these optimal conditions, providing design-relevant insights for future fuel-cell-powered aircraft.

2. Methodology

A reduced-order analytical framework is developed to describe the coupled aero-thermodynamic behaviour of ram-air cooling channels. The model is formulated based on conservation of mass, momentum, and energy, and decomposes the system into four principal components: inlet, diffuser, heat exchanger (HEX), and outlet nozzle. In the loss-free limit, the Meredith effect is derived as fundamental relationship of Brayton-cycle and propulsive efficiency.
Building on this idealized formulation, loss mechanisms are systematically incorporated. Diffuser losses are modelled using established pressure recovery correlations as functions of area ratio AR and flow non-uniformities. Heat exchanger performance is represented using the ε–NTU methodology, while associated pressure losses are captured via the Chilton-Colburn analogy, linking friction and heat transfer. This approach enables a generalized characterization of HEX behaviour independent of specific geometries.
The analysis identifies key non-dimensional parameters governing system performance: (i) diffuser loss coefficient, (ii) HEX goodness factor, (iii) HEX effectiveness, and (iv) inlet matching factor. A parametric study is performed over relevant flight conditions, including fuel cell operating temperature, Mach number, altitude, diffuser efficiency, and heat exchanger performance. The framework allows for the isolation of individual loss contributions and the quantification of their interactions. Furthermore, optimal operating conditions are determined by maximizing net propulsive (Meredith) efficiency, subject to realistic constraints on heat transfer and pressure losses.

3. Results / Conclusions

Figure 1 presents the absolute value of the ram-air channel efficiency $|\eta| = |F|v_\infty/\dot{Q}$, as a function of the diffuser area ratio AR, with solid and dashed lines indicating thrust and drag, respectively. For each area ratio AR, efficiency η is maximized with respect to HEX effectiveness ε, with the corresponding optimum ε^* shown in Figure 1b.
A reference case is compared against ideal diffuser, ideal heat exchanger, and higher Mach number conditions.
The results reveal three dominant regimes: Without diffusion, drag power remains on the order of the heat rejection. At low area ratios ($\mathrm{AR} < 10$), performance is governed by heat exchanger losses, which decrease quadratically with the area ratio due to reduced inlet velocity. Around $\mathrm{AR} \approx 10$, net drag vanishes as the Meredith effect compensates diffuser and HEX losses. At higher area ratios, net thrust becomes achievable, with performance increasingly limited by diffuser losses and the theoretical Meredith limit, while HEX losses become negligible.
Overall, the analysis highlights the strong sensitivity to design choices and shows that deviations from optimal conditions lead to significant efficiency penalties. The derived scaling relations provide a consistent framework for identifying optimal aero-thermal integration strategies.

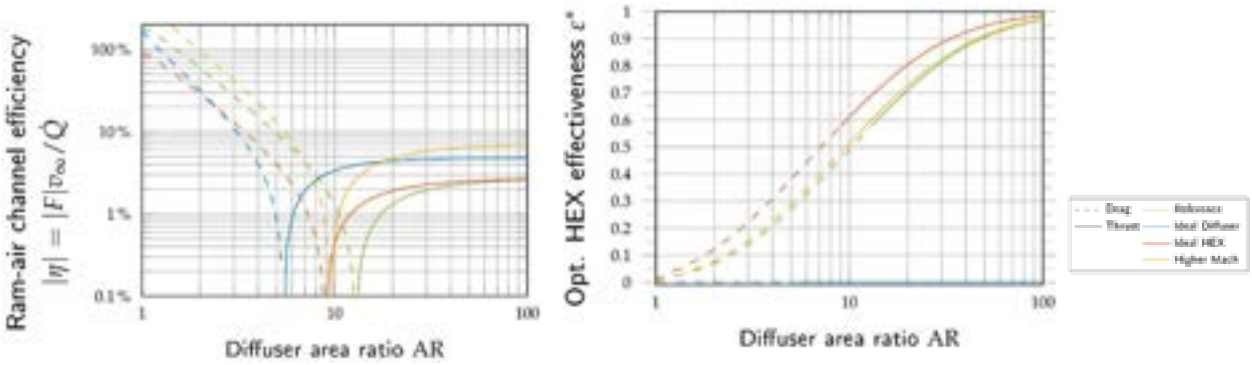


Figure 1. *(**a**) Ram-air channel efficiency depending on the area ratio AR; (**b**)* Optimum *HEX effectiveness ε*.*

Rear-Fuselage Integrated Surface Heat Exchanger for Fuel Cell Cooling in Regional Aircraft

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1. Introduction

Due to efforts to reduce the climate impact of aviation, multiple technological pathways are being investigated, including the increasing electrification of propulsion in aircraft, where electric machines provide or supplement mechanical shaft power within the powertrain. Within this context, the DOXWING project analyzes a year 2040+ box-wing aircraft design coupled with distributed electric propulsion (DEP). The required power is generated by fuel cells located in the aft section of the fuselage, directly in front of two liquid hydrogen tanks. Despite the relatively high efficiency of fuel cell systems, a significant amount of waste heat is generated. Compared to Brayton-cycle engines, where a substantial portion of the heat is dissipated through the exhaust flow at high temperature, fuel cell systems operate at considerably lower and more strictly defined temperature levels. This limits the available temperature difference between the cooling system and the ambient air and therefore requires an active thermal management system (TMS).

2. Methodology

Conventional heat rejection is typically achieved by ram-air heat exchangers (RHEXs). The combination of small temperature differences and high heat loads in the order of Megawatts for regional aircraft can result in large heat exchange areas required and therefore increased mass and drag. Surface heat exchangers (SHEXs) offer a compelling alternative by integrating cooling directly into the aircraft's skin. A SHEX consists of coolant channels embedded beneath the aircraft skin, transferring heat by conduction to the outer skin where it is dissipated to the ambient. When this concept is integrated into the aircraft fuselage, this refers to a fuselage integrated surface heat exchanger (FISH). The FISH concept is investigated to reject the waste heat generated by the fuel cell system across different

flight conditions. Furthermore, the heat rejection from the fuel cell system is decoupled from that of the electric components located in the nacelles at the wing. Depending on the required heat rejection capability, the FISH may be either used as a standalone TMS approach or combined with a conventional RHEX in a hybrid architecture. In such a configuration, the RHEX can be sized to handle situations where peak heat loads appear or serve as a complementary heat rejection TMS. Furthermore, when sufficient heat can be dissipated by the FISH, the RHEX operation may be adjusted at specific operating points, for example by reducing or even closing the ram-air flow path. For the studies, a suitable surface area on the aircraft's skin is first selected for the FISH, depending on different aircraft constraints. The TMS is then modeled using an in-house tool, which follows the methodology described in previous works . The resulting FISH-based TMS concept is then compared to a RHEX-only solution. To ensure a consistent and conservative comparison, the heat load from the fuel cell is considered without using the liquid hydrogen fuel as an additional heat sink.

3. Results & Conclusion

It is expected that, depending on the operating conditions, FISH can either serve as a supplementary cooling strategy or fully replace conventional TMS solutions for fuel cell systems on regional aircraft. In cruise, where the system is sized to exploit the available fuselage surface area and ambient flow conditions, the FISH is expected to fully dissipate the heat load without additional RHEX operation. For off-design operation at higher thermal loads or reduced heat rejection capability, the RHEX can be activated as an additional cooling device. This hybrid operation is expected to reduce aerodynamic drag during cruise and other low-power operating points, while eventually decreasing the overall mass of the TMS compared to a RHEX solution. The results indicate whether FISHs can serve as a supplementary cooling strategy or replace conventional RHEX TMS solutions. Furthermore, this work provides an initial step towards an aircraft-level integration of SHEXs within a distributed TMS.

Acknowledgment: The project underlying this report was funded by the Federal Ministry for Economic Affairs and Climate Action under the grant number 20M2246C "DOXWING". The responsibility for the content of this publication lies with the authors.

Thermal Performance Assessment of a Capillary Jet Loop Passive System for Air Supply Motor Power Electronic Powertrain Cooling in Hybrid-Electric Aircraft

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1. Introduction

In the proposed paper, a novel flat "-dcc box" component of a Capillary Jet Loop architecture (CJL-dcc) is proposed to passively transfer up to 20% of a heat load mimicking

the dissipation of an electrical subsystems of a short/medium-range aircraft with hybrid electric power and propulsion systems . The two-phase ring (TPR) provides the liquid to several capillary structures that induce vapor jets thanks to a manifold with five injectors. The momentum exchange between the high velocity acetone vapor flows and the low velocity of the subcooled liquid ensures both transport and condensation functions. This paper discusses the design, material and experimental performances of the TheMa4HERA demonstrator able to passively transfer up to 1.93 kW from 9 distributed hot sources. The influence of the roll angle (+/- 25°), the pitch angle (-20°/+35°) and the coupling with the evaporator of the Mechanical Pumped Loop evaporator are presented and analyzed.

2. Methodology

The proposed paper will describe the 3D thermal simulations on each component of the power electronic box used to size the flat -dcc box element. As described in Figure 1, this architecture creates a convenient thermal bus provided that the secondary heat load (HL_2) is synchronized with the main heat load applied (HL_1).

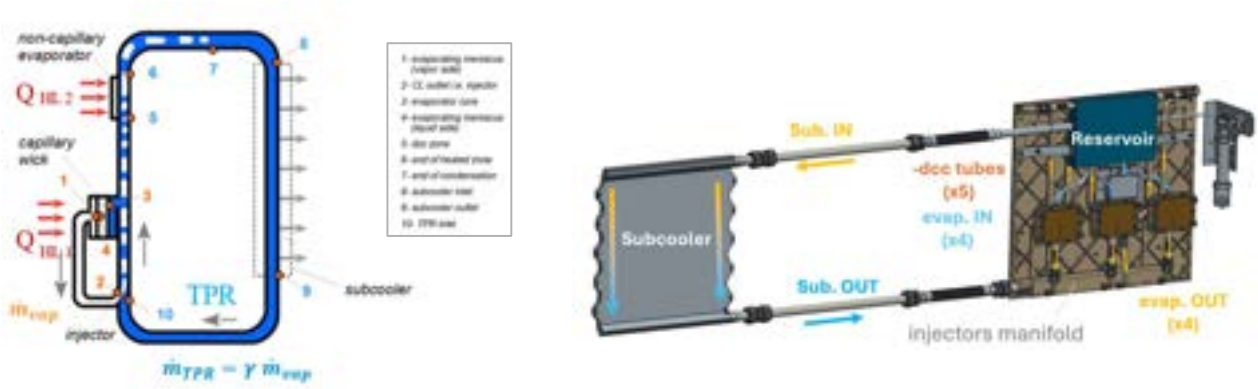


Figure 1. *Capillary Jet Loop in direct contact condensation, working principle (left) adaptation to the T4H demonstrator (right).*

The choice of the innovative passive thermal heat transfer architecture with be also explained with the main outcomes of the qualification test campaign performed with an air exchanger as a cold source and . The impact of lines length and inclinations will be shortly presented to better focus on the specific behavior on the MPL/CJL coupling return of experience. Considering the transportation constraints of the T4H demonstrator between partners sites, a specific heath monitoring methodology is given to anticipate an operational deployment of such a passive device containing an flammable fluid (acetone).

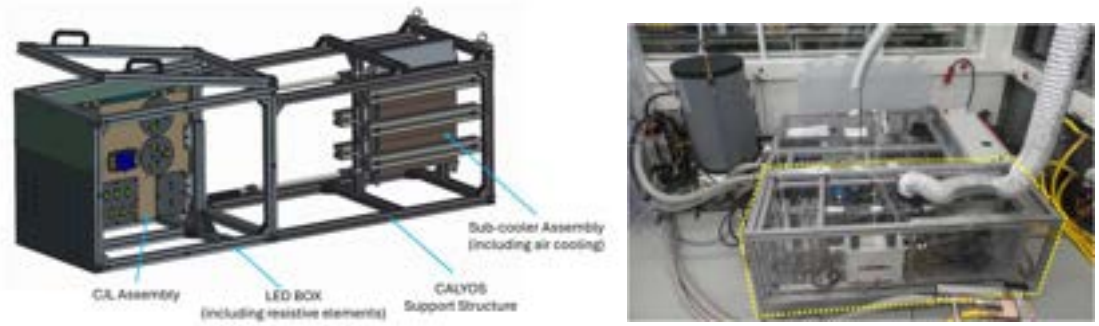


Figure 2. *CJL demonstrator (0.5m lines version), location inside the T4H MPL demonstrator: qualification with air exchanger (left) and integration inside the MPL demonstrator in NLR demonstration before shipping the system for final integration (right).*

3. Results / Conclusions

The present study demonstrates at TRL 4/5 the capability of a passive CJL to cool up to 20% of the total heat load, 1.93 kW, directly on the contact of a flat -dcc box component. It is the first time that a flat -dcc box component is used for thermal management of multiple hot spots. The overall thermal resistance is driven by capillary evaporator #8 temperature and the activation of the -dcc box sources improves the performance for the tested sharing factors (from 100% to 82.8%). The CJL is now able to operate in steady state with -20° pitch. Several ways to extend pitch operating range are under investigation; (i) choose an alternative fluid to acetone optimized for CJL -dcc thermal architecture, (ii) consider a variable section injector to improve the jet pump efficiency in hot condition, (iii) add a mechanical pump, with few Watts of electrical consumption and without control needs thanks to direct contact subcooling condensation feature.

Results of Scaled Test Program on Skin Heat Exchanger for Thermal Management in Hybrid Electric Regional Aircraft

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1. Introduction / Objectives

The development of Hybrid Electric Regional Aircraft (HERA) requires proposing advanced heat exchanger designs able to dissipate heat loads of the order or 1 Mw while minimizing space, weight, and aerodynamic penalties. Skin heat exchangers (SHX) based on a cooling fluid that undergoes phase change and which use the airflow over the aircraft for heat dissipation purposes are being considered as a promising concept to partially address this challenge . A critical aspect to validate this technology involves characterizing the airflow heat dissipation potential in an environment able to reproduce the expected flight conditions found in HERA operation. Based on a previous study , a systematic experimental program has been undertaken in a low speed wind tunnel facility to quantify the heat exchange process taking place over the turbulent boundary layer of the HERA skin, aimed at obtaining dimensionless heat transfer parameters in relevant flight operating conditions.

2. Methodology

The test-bench used to carry out the SHX experimental program is the BV4 low-speed wind tunnel at Universidad Politécnica Madrid (UPM), having a 1×0.75 m cross section and a top free stream velocity of 40 m/s (Figure 1).



Figure 1. *SHX/airflow scaled test set up. Left: wind tunnel general view of inlet and test section. Right: detail of the SHX scaled prototype mounted in wind tunnel.*

The SHX prototype tested in this facility includes eight streamwise oriented cooling channels and is a 2:1 scaled version of a preliminary configuration considered for the HERA flight operation. The wind tunnel scaled tests conditions have been established by combined use of dimensional analysis arguments and CFD numerical simulations to validate physical similarity between the low speed, near standard pressure and temperature conditions characterizing the wind tunnel operation and the HERA flight environment . For the SHX to airflow heat dissipation characterization, the cooling channels are fitted with electrical resistances whose feeding power can be precisely monitored. The approaching flow momentum and thermal boundary layers are characterized by normal to wall traverses that include thermocouple thermometry as well as pneumatic and hot-wire anemometry in different spanwise locations. The SHX thermal characterization is achieved through airflow and cooling channels wall thermocouples as well as infrared (IR) thermography of the airflow exposed wall. Data postprocessing is performed in order to obtain the streamwise resolved map of the SHX to airflow Stanton number characterizing each SHX cooling channel, allowing the characterization of both streamwise and spanwise end effects in the SHX to airflow heat dissipation process. By controlling the wind tunnel airspeed and the power input to the

electrical resistances the approaching boundary layer Reynolds number and the SHX wall to airflow temperature ratio can be independently varied, thus allowing the characterization of the SHX to airflow Stanton number as a function of the key dimensionless parameters determining the SHX to airflow heat transfer process.

3. Results / Conclusions

The streamwise evolution of the SHX/airflow Stanton shows three different, well defined regions along the streamwise coordinate, corresponding to the enhanced heat transfer taking place at the SHX leading and trailing edges, as well as an intermediate streamwise region where the SHX to airflow heat transfer takes place through conditions approaching a well-developed momentum and thermal boundary layer. In addition, the scaled tests allow characterizing the spanwise modulation of the Stanton number, clearly identifying the spanwise scale involved in the enhanced heat dissipation linked to spanwise end effects. Postprocessing of data obtained under different Reynolds number and SHX wall to external flow temperature ratio allows characterizing the SHX/airflow heat exchange process under a range of different flight operating conditions and proposing relevant scaling laws for the SHX to airflow heat transfer process.

Cryogenic thermal conductivity of additively manufactured ceramics for thermal management components

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1. Introduction / Objectives

Advances toward hybrid-electric and hydrogen-powered aviation are broadening the temperature window over which thermal management components must operate, spanning from gas turbine environments to cryogenic hydrogen storage. Within this range, thermal conductivity emerges as a decisive material property, as it governs both the achievable heat-transfer performance and the fin effectiveness of compact, additively manufactured architectures. Conventional metallic alloys are constrained by their density, restricted service temperatures and susceptibility to hydrogen embrittlement. In this context, 3D-printed technical ceramics, specifically aluminum oxide (Al_2O_3) and aluminum nitride (AlN) shaped via Lithography-based Ceramic Manufacturing (LCM), emerge as candidate materials whose conductivity profiles may complement or surpass those of metals in selected operating regimes . This work investigates the cryogenic thermal conductivity in the temperature range from 20 K to 293 K, for which reliable data on ceramics are still scarce.

2. Methodology

Cylindrical samples with a diameter of 10 mm were manufactured from aluminum oxide (Al_2O_3, LithaLox 350, 99.8% purity) and a pre-series aluminum nitride (AlN) material using Lithography-based Ceramic Manufacturing (LCM), an additive manufacturing process

enabling high-resolution fabrication of technical ceramic components. Following printing, the green bodies underwent debinding and subsequent pressureless sintering under material-specific conditions. Al_2O_3 samples were sintered in air at temperatures up to 1700 °C, while the AlN specimens were sintered under protective nitrogen atmosphere at temperatures up to 1840 °C to prevent material degradation and oxidation. To investigate thermal conductivity behavior and distinguish between bulk material and interface-related contributions, specimens with two different heights (3 mm and 6 mm) were manufactured and subsequently tested in the cryogenic thermal conductivity test setup shown in Fig. 1.

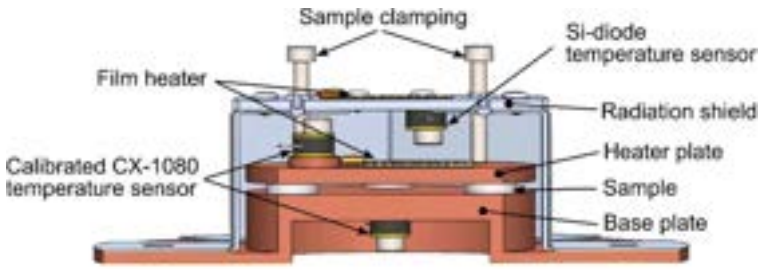


Figure 1. *Schematic of the test setup.*

Three samples are mounted in parallel between two copper plates using indium as thermal interface. The base plate is mounted to an ARS DE-204 cryocooler, and the heater power necessary to maintain a constant temperature difference over the samples is measured at the heater plate. A temperature-controlled radiation shield prevents heat inleak to the heater plate. Measurements are performed between 20 K and 293 K. Analysis of the two sample thicknesses allows the interface and bulk material conductivities to be separated.

3. Results / Conclusions

The developed test setup enables steady-state thermal conductivity measurements of additively manufactured technical ceramics between 20 K and 293 K. Using two different sample lengths allows the contact resistance at the indium interfaces to be separated from the bulk material contribution, which is essential at cryogenic temperatures, where interface effects can dominate thermal resistance. For LCM-printed Al_2O_3, the obtained conductivity values lie within the broad scatter band of literature data summarised by Ghavami and Ghiaasiaan and reproduce the characteristic low-temperature peak near 70 K. Ongoing measurements on LCM-printed AlN are expected to confirm its significantly higher conductivity over the same range. These findings support the use of 3D-printed technical ceramics as candidate materials for compact heat exchangers in hydrogen conditioning systems.

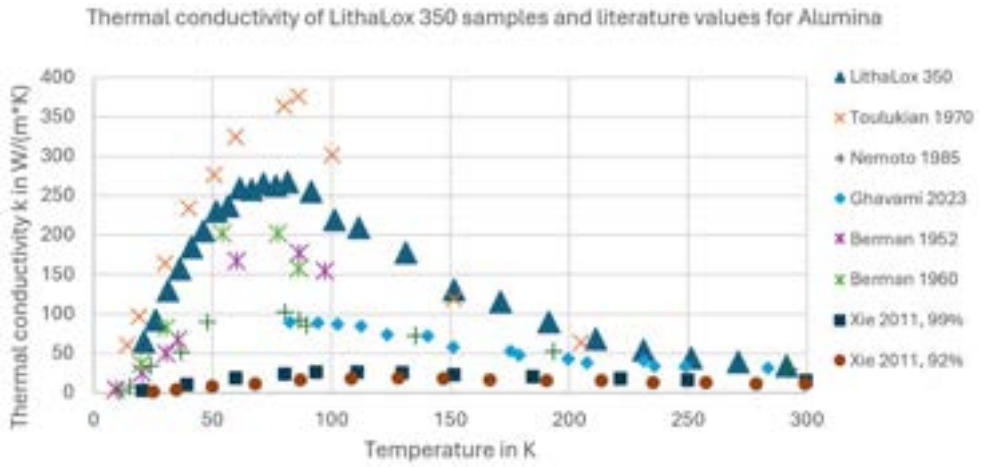


Figure 2. *Thermal conductivity of Al_2O_3 between 20 K and 300 K.*

Acknowledgement: This project has received funding from the European Union's Horizon Europe Research and Innovation programme under grant agreement No 101138960, project TRIATHLON.

Experimental Assessment of an Electrical Temperature Control System with Carbon Heating Duct Technology for More-Electric Aircraft Cabins

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1. Introduction / Objectives

The transition toward more-electric aircraft requires alternatives to conventional bleed-air-based cabin heating that improve efficiency, controllability, and integration flexibility. Within the Clean Aviation TheMa4HERA project, this study evaluates an electrical Temperature Control System (eTCS) that uses distributed carbon-based resistive heating elements integrated directly into cabin ducting. The objective is to assess the thermal behavior, controllability, and cabin-level impact of this concept under representative aircraft operating conditions. Emphasis is placed on its ability to provide homogeneous heat delivery, reduce local thermal discomfort, and maintain stable performance under adverse external boundary conditions. The work addresses both system-level and local thermal effects, thereby contributing experimental evidence for the feasibility of electrically driven cabin heating architectures in next-generation more-electric aircraft.

2. Methodology

A two-level experimental methodology was applied to evaluate the eTCS. First, system-level tests were performed at the Fraunhofer Flight Test Facility using a full-scale forward cabin section of a twin-aisle aircraft. In this setup, carbon heating elements were integrated into the main supply ducting supplying the cabin ceiling inlet. Realistic aircraft environmental conditions were reproduced by adjusting airflow rates, operating pressures, supply

temperatures, and external skin temperatures. Electrically heated passenger dummies simulated internal loads. The cabin was instrumented with air temperature sensors at multiple seat rows, heights, and ceiling inlet positions for environmental assessment.
Second, local investigations of carbon heating in riser ducts were conducted in the Lining and Insulation Test Environment (LITE) chamber under controlled thermal boundary conditions. The test matrix included ground-like and flight-representative cases with variations in external skin temperature, airflow through the riser duct, heater power, and insulation configuration. Steady-state operating points were used for comparative evaluation. Measurements included inlet and outlet air temperatures, local air temperatures in adjacent structural regions, duct surface temperatures, and heat loss estimates. Infrared thermography complemented the sensor data to visualize spatial temperature distributions and to compare heater-on and heater-off conditions. Together, the full-scale cabin and chamber campaigns enabled assessment of thermal uniformity, response behavior, and controllability at both cabin and component level.

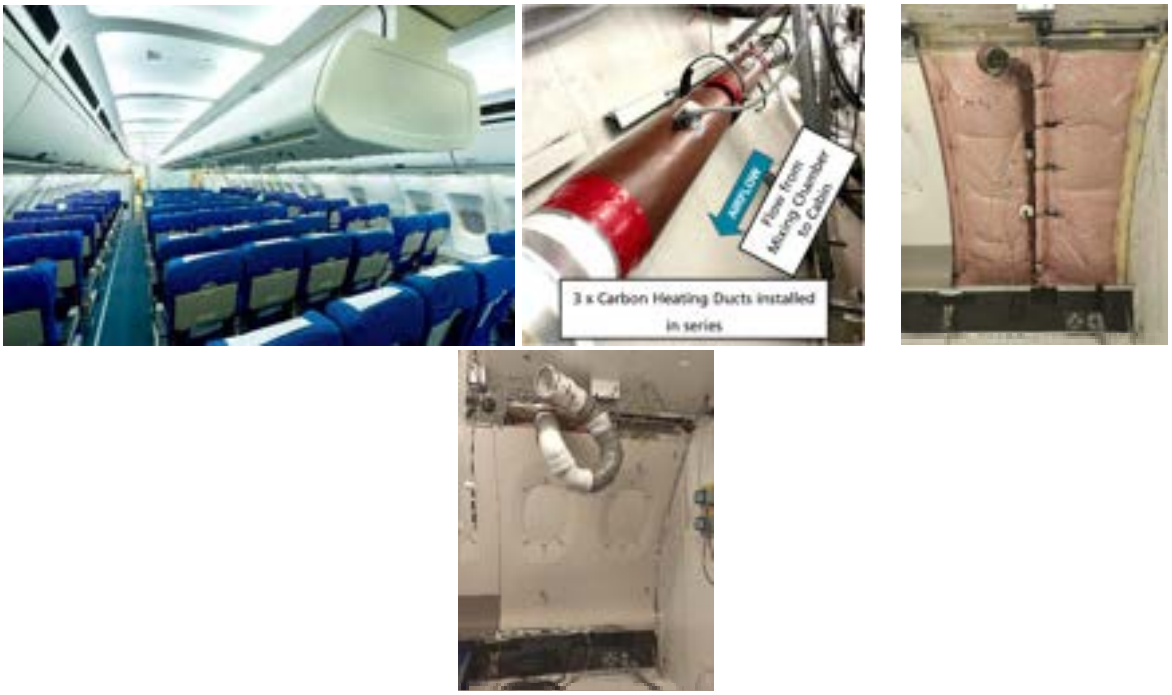


Figure 1. *Left: Cabin Demonstrator and main duct eTCS, Right: Riser duct eTCS integration and lining installation*

3. Results / Conclusions

The experiments demonstrate that carbon-heated ducts provide measurable, spatially uniform heating of cabin supply air. Under both ground and simulated flight conditions, the system maintained stable thermal output and showed robust performance even at low external skin temperatures. Infrared imaging and sensor data confirmed homogeneous duct surface heating and reduced cold zones near ceiling inlets. Owing to the low thermal inertia of the carbon heating elements, the system responded rapidly to power adjustments, enabling precise control of cabin conditions. Overall, the results confirm the technical feasibility of electrically heated carbon duct technology as a promising solution for more-

electric aircraft, offering localized heat generation, improved zonal controllability, and reduced dependence on engine-derived thermal energy.

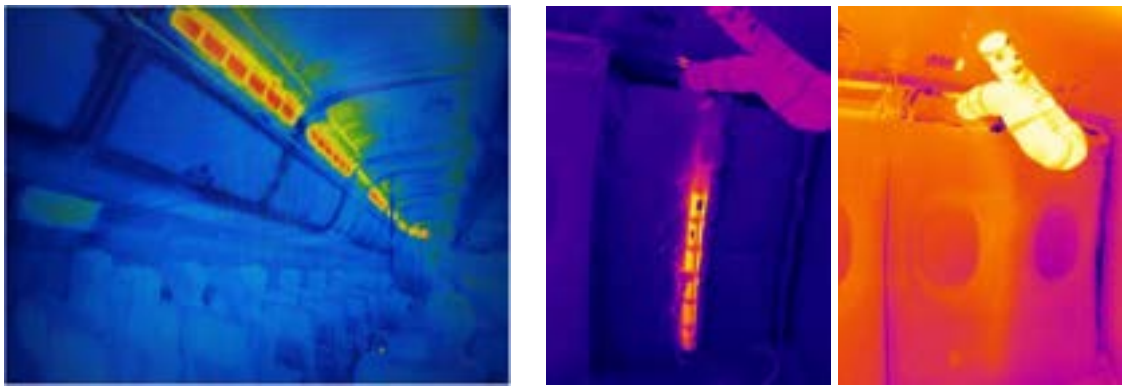


Figure 2. *Left: Effect of main duct eTCS heater on air outlets in cabin, Right: Thermal image of Riser duct eTCS. Without and with lining*

Avionics Heat Reuse for Cargo Heating

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[2] Nord-Micro, Germany

1. Introduction / Objectives

This study investigates whether waste heat generated by aircraft avionics can be reused to heat the forward cargo compartment and thereby reduce or replace trim-air demand. The concept is particularly relevant for future hybrid-electric aircraft, where every unit of recoverable thermal energy can improve overall system efficiency. In the proposed approach, warm air from the avionics bay is redirected beneath the cargo floor through a perforated Piccolo ducting system installed in the bilge. Compared with conventional architectures that reject avionics heat and rely on separate heating systems, this approach enables direct thermal energy recovery within the environmental control system. The objective of the work is to quantify the achievable heating contribution under representative ground and flight conditions and to assess the influence of airflow routing and operating parameters on cargo-compartment thermal performance.

2. Methodology

The investigation was carried out in the Fraunhofer Flight Test Facility using a full-scale forward fuselage mock-up of a wide-body aircraft, including cockpit, forward cabin, avionics bay, bilge, and a forward cargo hold representative of the target configuration. The mock-up is installed in a low-pressure chamber that can reproduce cabin pressure profiles for complete flight cycles, while a surrounding cladding system allows controlled simulation of external thermal conditions on the aircraft skin. To emulate avionics thermal loads, extracted cabin air

was heated by electrical heaters and routed into the bilge, where perforated Piccolo ducts distributed the warm air beneath the cargo floor (Figure 1). A cargo air extraction system was installed near the cargo door to emulate cargo air leakages, thereby enabling the evaluation of the heat transferred into the compartment air. Measurements included air temperature and mass flow at key positions along the extraction, fan, heater, and Piccolo flow path as well as within the cargo compartment. In addition, convective heat transfer meters were installed on the cargo floor to determine local heat transfer coefficients, and an infrared camera recorded spatial floor temperature distributions during steady-state operation. The test matrix covered in-flight and on-ground conditions, varying cabin pressure, skin temperature, total thermal input, Piccolo airflow rate, cargo ventilation, and duct orientation to compare the baseline configuration with alternative heat-distribution concepts.

3. Results / Conclusions

The experiments show that avionics heat reuse provides a measurable contribution to the cargo compartment (Figure 2) under both flight and ground conditions. Heat transfer into the cargo hold was confirmed by air-temperature-based evaluations and by cargo-floor heat-balance measurements, with both methods showing generally consistent trends. Comparisons between configurations indicate that redirecting the duct toward the aircraft skin does not significantly degrade heating relative to directing it toward the cargo floor. In contrast, increasing the Piccolo airflow rate can reduce heating effectiveness because the lower outlet air temperature offsets gains in convective transfer. Even without active cargo ventilation, a residual heat ingress into the cargo hold was observed. Overall, the results provide experimental evidence that avionics waste heat can serve as a useful supplementary or replacement heat source for cargo heating, supporting more energy-efficient thermal management concepts for future hybrid-electric aircraft.

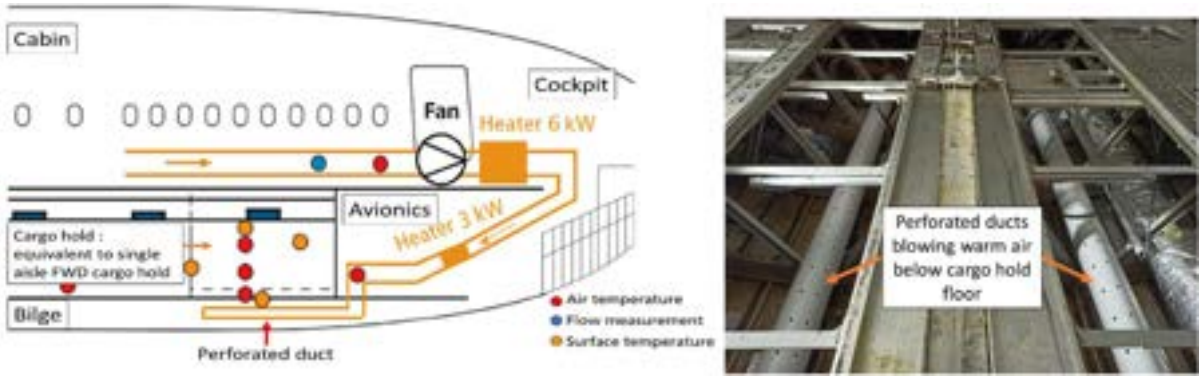


Figure 1. *Schematic of the avionics heat reuse concept and its integration beneath the forward cargo floor.*

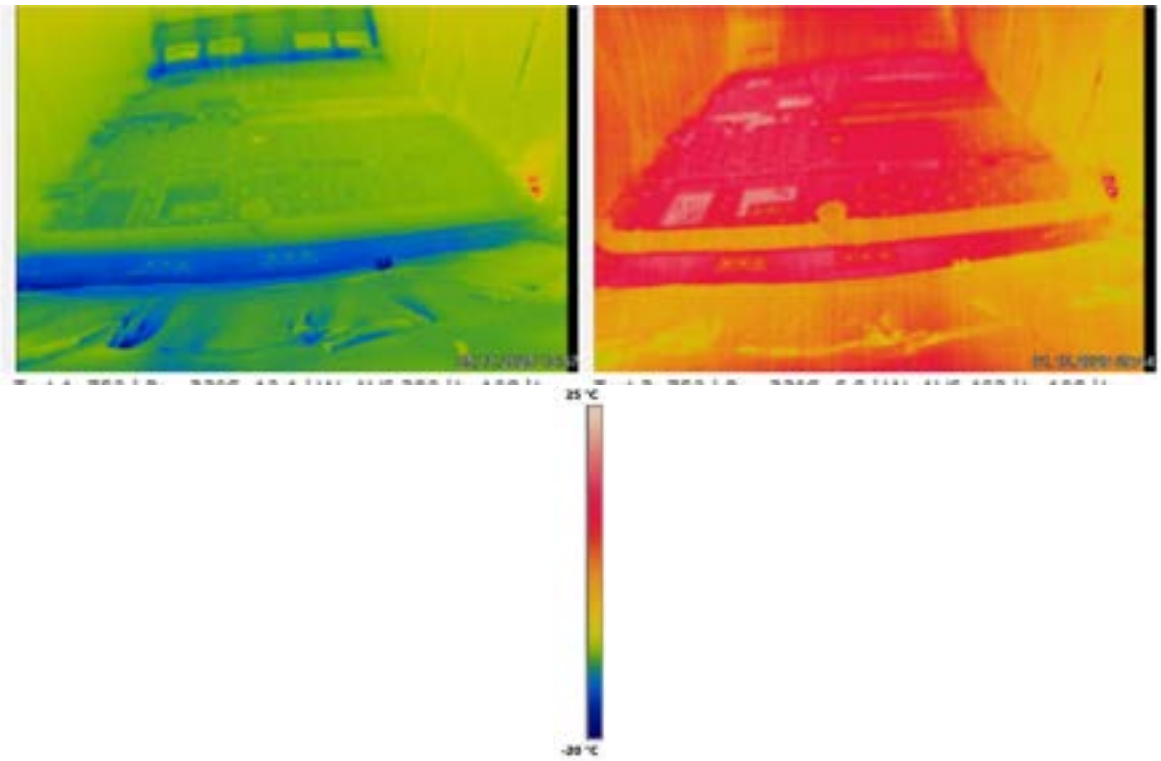


Figure 2. *IR images of the cargo floor in baseline test (left) and when operating the avionics heat reuse system (right).*

Engine Waste Heat Usage by Energizing the Bypass Flow Using Surface Turbulators

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1. Introduction / Objectives

To build more efficient aircraft in the future engineers need to optimize aircraft as one system of airframe and engine instead of individual components. Within the collaborative research centre TRR 364 "SynTrac" we investigate the synergy effects in highly integrated transport aircraft due to interactions of propulsion and airframe.
In case of a more electric turbofan, the low-temperature waste heat produced by electric components and due to friction in the engine's bearings should be used. The bypass flow has a significant pressure ratio to ambient and a favourable temperature difference to the temperature the heat is produced at. This makes the bypass duct an ideal heat sink as some part of the waste heat could be used to generate thrust. So far only attempts to include surface coolers in the bypass duct are known , . For the SynTrac project however, the inner wall of the bypass duct is investigated to act as a surface heat exchanger. To increase the heat transfer, small turbulation structures such as dimples, protrusions and ribs (see Figure 1) are investigated numerically regarding their heat transfer enhancement with respect to the additional pressure losses.

2. Methodology

To get a comparison of the different heat transfer enhancing structures, a hydrodynamically fully developed channel flow is used. The channel consists of a slot between two parallel plates with a distance of $H = 0.1\ \mathrm{m}$ and can be seen in Figure 1.

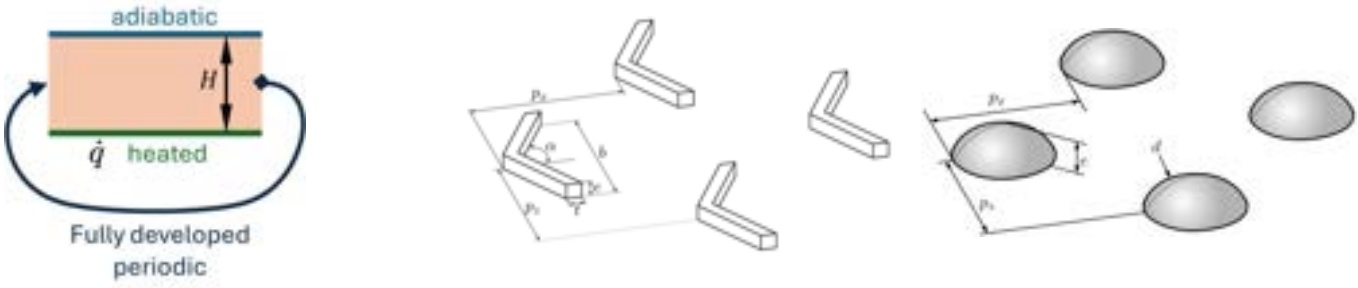


Figure 1. *Simulation domain and exemplary structure types under investigation (V-ribs and protrusions)*

Reynolds Averaged Navier-Stokes (RANS) simulations for a fully-developed periodic segment are performed. The flow conditions in the channel are set similar to the bypass flow at cruise (pressure, density, temperature, mass flux, Mach number) resulting in a Reynolds number of $\mathrm{Re_D} = (\rho \overline{u} D_\mathrm{H})/\mu = 710{,}000$. These conditions are untypical for heat transfer enhancing structures and therefore not much data exist.
Due to heat transport issues, only the inner wall of the engine is supposed to be heated. Thus, the bottom wall of the periodic channel sees a constant heat flux $\dot{q}$, whereas the top wall is kept adiabatic.
The flow and the heat transfer are simulated to obtain the Nusselt number $\mathrm{Nu} = (hD_\mathrm{H})/k$ and Darcy friction factor f_D of each configuration. A reference channel with a smooth bottom wall serves as the reference for the turbulator geometries. Additionally, the Dittus-Boelter and Gnielinski Nusselt correlations are used as a reference for the Nusselt numbers, e.g. $\mathrm{Nu_0}$. The increase in the Nusselt number ratio $\mathrm{Nu}/\mathrm{Nu_0}$ and friction factor f/f_D are then compared to identify the best performing geometry.
Turbulators for heat transfer cause unsteady secondary flows that are difficult to resolve just by using RANS. The numerical level of fidelity is thus increased to URANS and the obtained increases of heat transfer enhancement and friction factor are compared to the RANS solutions. Additionally, the sensitivity of the used turbulence model as well as the grid type is investigated.

3. Results / Conclusions

We can show in the first RANS solutions obtained that all of the investigated geometry types are capable of increasing the heat transfer at the flow conditions in the bypass duct as shown in Figure 2. The small protrusions investigated did not increase the heat transfer enhancement. Dimples and protrusions with a height $e = 5\ \mathrm{mm}$ perform better than ribs to increase heat transfer with respect to the increase in friction factor as seen by the larger thermal hydraulic performance (THP). Therefore, ribs are excluded from further studies as the friction penalty is too high. Simulations with URANS are ongoing.
In the future, it is planned to further increase the level of fidelity to DES in order to better

resolve the secondary flows. Additionally, a cooperating project will use the results of these studies to investigate the performance inside the bypass duct geometry.

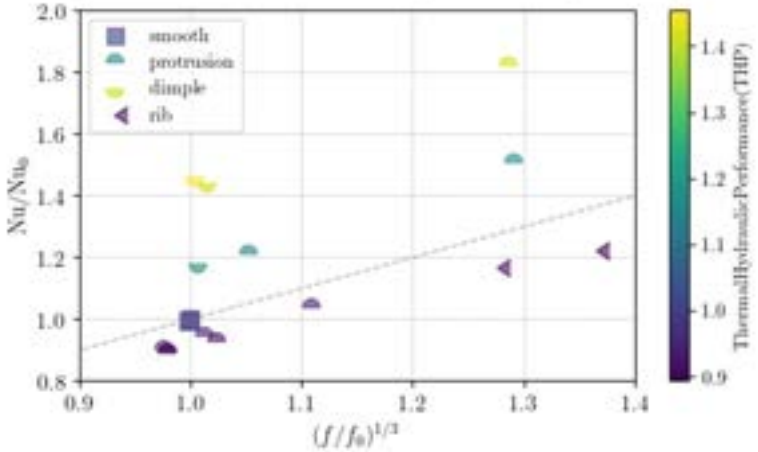


Figure 2. *Heat transfer enhancement and friction factor results obtained from RANS simulations for different structure types and sizes.*

Development and testing of a lightweight two-phase pumped cooling system for aviation fuel cells in the BRAVA project

Henk Jan van Gerner[1], Georg Mühlthaler[2], Marcus-Benedict Buntz[3]
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[2] Airbus, Germany
[3] Aerostack, Germany

1. Introduction / Objectives

Hydrogen-powered fuel cells are the preferred energy source for electric aircraft. For aircraft application, it is of upmost importance to reduce the mass of the fuel cell cooling system. For this reason, a novel lightweight two-phase pumped cooling system is being developed in the EU funded BRAVA project. This system uses the evaporation of methanol (the term 'two-phase' refers to the phase transition of the fluid from liquid to vapor), which can result in a mass saving of 1600 kg for a 100 passengers aircraft with four engines compared to a conventional liquid ethylene glycol water (EGW) cooling system . The two-phase cooling part of the project has two main objectives:

1. Built and test a lightweight two-phase pumped cooling system with 240 kW cooling capacity. This system uses electric heaters to emulate the heat load of a fuel cell system
2. Built and test a small (few kW) fuel cell stack that is cooled with a two-phase cooling (2-PC) system in order to demonstrate the compatibility of 2-PC with a fuel cell stack

2. Methodology

A 240 kW system has been designed with NLR's cooling system analysis tool. Figure 1 shows a photo of the system. A small pump (with a mass of 2 kg and a power of 300 W) transports liquid methanol to the evaporator section, where electric heaters emulate the heat load of a 240 kW fuel cell stack. In this evaporator section, the heat is transferred to the methanol, and the liquid (partly) turns into vapour. The vapour/liquid mixture then flows to the air cooled

condenser via a 7 meter long pipe. Air is forced through the condenser by a fan that is located outside the building. The absorbed heat from the heat source is transferred to the air and the vapour is turned back into liquid. The system has a liquid flowmeter, an air flowmeter and four sight glasses with cameras to monitor the flow. The fluid pressure is measured at 7 locations and a dp sensor is used to measure the air pressure drop over the heat exchanger. In order to investigate if two-phase cooling with methanol works with a functional fuel cell, a dedicated two-phase cooling system was built to cool a fuel cell stack in a fuel cell test bench at Aerostack, see Figure 2 for a photo.

3. Results / Conclusions

A 240 kW heat load was cooled with the two-phase pumped cooling system and the test results are in good agreement with the simulation results. Also, a fuel cell stack was cooled with a two-phase cooling system and all operating conditions showed stable operation and good cell voltages homogeneity. At system maximum power condition, approximately 3 kW of waste heat is generated by the fuel cell stack which is cooled by the 2-PC system. The successful tests with the 240 kW two-phase cooling system and two-phase cooling of a functioning fuel cell successfully verified the feasibility of this new technology.

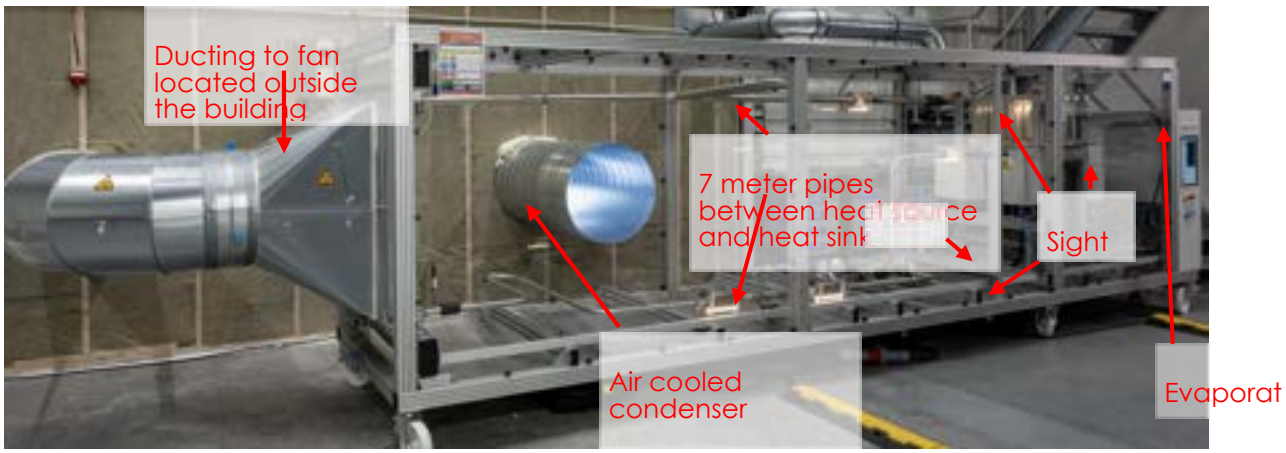


Figure 1. *Photo of the 240 kW two-phase cooling system.*

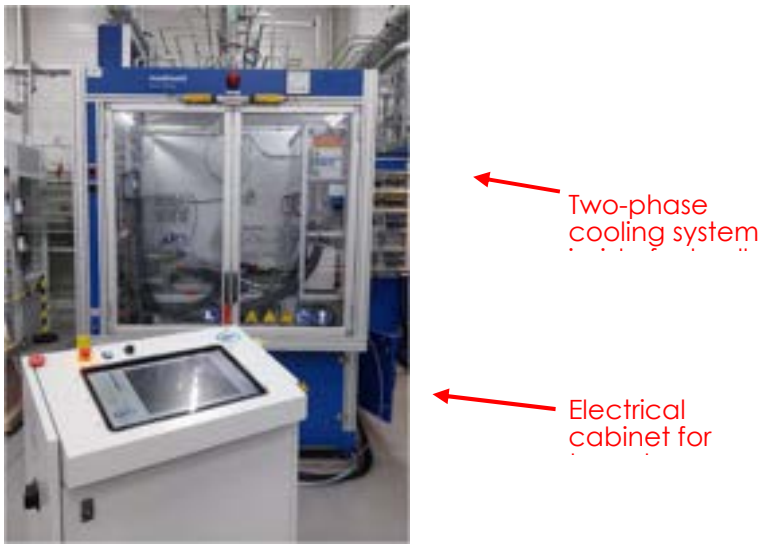


Figure 2. *Photo of the two-phase cooling system inside the fuel cell test bench at Aerostack*

Acknowledgement: The BRAVA project is funded by the European Union's Horizon program under grant agreement number 101101409. This publication reflects the authors' views. Neither the European Union nor the Clean Hydrogen Joint Undertaking can be held responsible for them.

Flight and Wind Tunnel Performance Characterization of a Structural Folded-Core Composite Skin Heat Exchanger Using Temperature-Sensitive Paints

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University of Stuttgart, Germany

1. Introduction / Objectives

The increasing electrification of aviation introduces low-temperature waste heat as a primary thermal management challenge. Conventional ram-air coolers dissipate this heat effectively, but impose a significant drag penalty incompatible with the efficiency goals of small electric and hybrid aircraft. Structure-integrated skin heat exchangers (SHXs) combining folded cores with carbon fiber-reinforced polymer (CFRP) facesheets offer an aerodynamically integrated, large-area, low-pressure-loss alternative . The pronounced thermal anisotropy of CFRP facesheets enables targeted lateral heat spreading and represents a key design parameter. Prior work established an analytical model demonstrating that optimal coolant channel spacing can increase mass-specific cooling efficiency by up to 12% . However, that model relied on a spatially averaged heat transfer coefficient and did not account for the directional dependence of convective transfer under real flight conditions. While wind tunnel scaling strategies for SHX validation have been demonstrated , experimental performance data from real composite prototypes under actual flight conditions remain scarce. The present work addresses this gap directly.

2. Methodology

The SHX investigated in this study has an active surface area of 0.45 m × 0.45 m and is manufactured as a folded-core sandwich panel. A Miura-ori fold pattern forms the core structure, generating a network of zigzag-shaped internal channels through which the liquid coolant is circulated. The outer facesheet consists of a four-layer silver-coated CFRP laminate, whose anisotropic thermal conductivity - high in the in-plane direction, low through the thickness - is deliberately exploited for lateral heat distribution. Depending on boundary conditions, this anisotropy yields different mass-optimal channel spacing configurations, which are the primary parametric subject of this study.

Flight experiment. A manufactured prototype is integrated into the hybrid-electric research aircraft eGenius operated by the Institute of Aircraft Design (IFB) at the University of Stuttgart. Coolant inlet and outlet temperatures as well as volumetric flow rates are recorded for each channel configuration, enabling determination of the total transferred heat flux as a function of the flight mission (airspeed, altitude, and ambient temperature). Three channel occupancy configurations are investigated — every channel, every second channel, and every third channel active — alongside at least one orientation variant in which the channels are aligned with, rather than transverse to, the external flow direction.

Wind tunnel experiment. A geometrically equivalent SHX model is constructed for wind tunnel testing, with the cooling channels represented by electrically heated copper tracks. The electrical power input serves as a precisely controlled and directly measurable heat flux boundary condition. Surface temperatures are measured using temperature-sensitive paints (TSP), and together with the freestream temperature as reference, a spatially resolved map of the local heat transfer coefficient $h(x, z)$is obtained across the full panel surface. The wind tunnel campaign covers the same channel configurations as the flight experiment, enabling direct comparison of total transferred heat flux between both setups. Additional configurations with channel spacing varied in increments of one-quarter channel width are included to extend the parameter space beyond what is accessible in the flight hardware. Both specimens are individual prototypes and may differ in facesheet thickness and laminate composition. These geometric deviations are characterized and their influence on the thermal response is assessed as part of the study.

3. Results / Conclusions

The dual-experiment approach enables a direct comparison between integral thermal performance under real flight conditions and locally resolved heat transfer characteristics obtained in the controlled wind tunnel environment. Flight measurements provide quantitative data on total heat dissipation across channel configurations and operating conditions, establishing a performance baseline for the manufactured prototype. Wind tunnel experiments complement this by resolving the spatial distribution of the heat transfer coefficient — the key quantity absent from the prior analytical model — and thereby exposing the influence of boundary layer development and flow directionality on overall SHX efficiency. Together, the two datasets allow the limitations of the spatially averaged model assumption to be quantified and provide improved boundary condition data for next-generation analytical and numerical models. The results are expected to inform the mass-optimal design of larger-scale SHX systems for future electric and hybrid aircraft platforms.

Computational Investigation of Oil Flow Characteristics for Lubrication and Cooling Optimization in a new complex aircraft transmission.

Helmut Mad, Gernot Burghard Hedjri-Peyfuss
TU Wien, Austria

1. Introduction

Highly efficient transmission systems play a key role in modern aerospace applications with focus to sustainability by increasing energy efficiency, power density, and operational reliability. However, the increasing complexity of modern propulsion systems also raises the demands on the tribological and thermal design of gearbox architectures. In particular, the optimal distribution of lubrication and cooling media significantly influences efficiency, lifetime, and thermal stability.
Load-independent power losses, such as oil churning and windage effects, are strongly linked to local lubrication and cooling injection points. Especially in complex multi-stage or planetary aerospace gearboxes, highly dynamic multiphase flow phenomena occur that are hardly to capture analytically.
The objective of this work is to predict the lubricant distribution which is directly linked to the efficiency, reliability, and thermal robustness of a future aerospace gearbox system, by using advanced numerical simulation methods to gain an on the edge of technology tailored lubricant and cooling system.

2. Methodology

To investigate the fluid-dynamic and tribological interactions, with focus to highly efficient aviation gearbox systems, numerical methods, particularly Computational Fluid Dynamics (CFD) analyses, are applied. The objective is to achieve the most realistic representation of complex multiphase oil flows and associated loss mechanisms inside the gearbox in order to carry out optimizations and make more accurate predictions
Conventional analytical approaches are limited due to geometric complexity of gearboxes and strong interactions between fluid flow, temperature, and rotating mechanical components. Especially in complex multi-stage or planetary gearbox architectures, transient multiphase flow effects occur that require numerical solution. A major challenge is the modelling of the complete gearbox at once as well the oil flow in the meshing gears.
Only a full-system simulation of interaction between rotating gearbox components, oil injection nozzles, and multiphase oil volume flows allows an adequately validation of a well-designed lubrication distribution system. Consequently, the simulation of the entire gearbox in sufficiently refined mesh resolution of the free flow volume and accurate representation of local oil injection phenomena is the target.
The resulting simulation model is computationally demanding and requires substantial computing power and memory resources. Nevertheless, this modelling effort is essential, since reliable conclusions regarding gearbox fluid dynamics can only be achieved if dominant dynamic flow effects and their interactions are realistic resolved.
The applied methodology enables detailed analysis of local oil distribution, vortex formation, parasitic loss mechanisms, and thermal interactions inside the gearbox. In particular, this complex fluid dynamics simulations are the most promising methods to allow investigation of interactions between oil flow and gearbox housing structures, as well as the influence of injector positioning on lubrication and cooling efficiency. Ideally a thermal simulation result can be used to evaluate the occurrence of local thermal hotspots under already

optimized/minimized oil flow conditions.
A minimum and still adequate volume flow definition of lubrication and cooling fluid seems the key feature to reduce the independent power losses inside the transmission.
The simulations were conducted by using the finite-volume CFD solver SIMERICS MP+ to dimension the oil injector outlet hole diameters which are directly linked to the oil jet mass flow.

3. Conclusions

CFD simulations enable detailed analysis of the local lubrication and cooling demand of loss-affected gearbox components. This allows to adjusted precisely oil volume flows accordingly to local tribological and thermal demands, significantly reducing unnecessary oil supply rates and associated parasitic losses.
Furthermore, the simulations support optimization of injector positioning. Flow-induced vortices may locally deflect oil jets and thereby reduce lubrication and cooling effectiveness. Such effects can be identified numerically and minimized through targeted design modifications. In addition, undesired interactions between oil flow and gearbox housing geometry can be reduced or even eliminated already in the design phase of the transmission.
The major outcome is the prediction and reduction of load-independent losses caused by oil churning, vortex formation, and excessive oil volume flows directly linked to unwanted splashing losses. The focus on applying this methodology was set to a complex aviation gearbox system, which is used in hydrogen-based propulsion concept with already increased thermal management requirements and as contribution to sustainable future aviation technologies.



Figure 1. *Planetary Gearbox oil and air splashing*

Demonstration and Performance Assessment of Two-Phase Cooling for Fuel Cell Stacks in Commercial Aviation

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[1] Aerostack, Germany
[2] Royal Netherlands Aerospace Centre (NLR), Netherlands
[3] Airbus, Germany

1. Introduction / Objectives

Enabling fuel cell (FC) powered aircraft propulsion systems motivates the development of novel lightweight thermal management solutions (TMS). A mechanically pumped two-phase cooling (2-PC) approach for fuel cell stack was investigated in the public funded project BRAVA and allows weight savings of -26% and up to -59% depending on architectures of the TMS compared to conventional liquid cooling systems . The work package's main objectives were to verify the feasibility of 2-PC and ensure an even temperature distribution (<±5K) across the active cell area and thus preventing hotspots.

2. Methodology

The study employed an experimental test campaign using an Aerostack short stack (9 cells), which was rigged into an existing FC test system adapted with an integrated small-scale mechanically pumped two-phase cooling (2-PC) loop developed by NLR. This integration served as an intermediate heat exchanger, enabling rapid test machinery modification for this campaign. After commissioning with a low-performance non-flammable coolant, the primary testing was conducted using Methanol, leveraging its high heat of vaporization to achieve saturated flow boiling within the Bipolar Plate coolant channels. The FC stack was operated across various relevant flight conditions, including idle and maximum power, to ensure stable two-phase coolant flow. A flow sight glass was installed for observation of the stack outlet flow regime and phase state, see Figure 1.

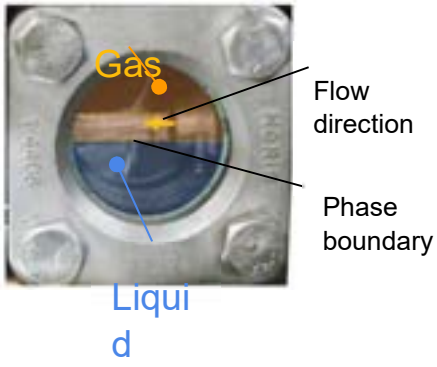


Figure 1. *Outlet flow sight glass with highlighted stratified two-phase flow for "Idle" operation condition.*

Measurements were performed using thermocouples and a device for local cell temperature distribution. The experimental data are then compared with results of our current fuel cell stack simulation model for validation.

3. Results / Conclusions

The demonstration successfully verified the feasibility of 2-PC with Methanol for a PEM FC stack, achieving stable operation across critical flight conditions. Temperature homogeneity within the target of ±5K was achieved and no liquid superheating effect was observed, see Figure 2 for along the channel temperature profile and heatmap of the cell.

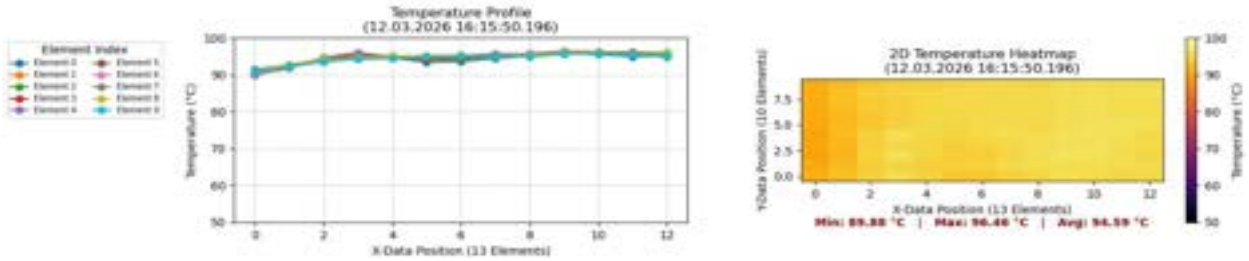


Figure 2. *Temperature profile along the channel (left) and heatmap of the fuel cell (right) for "Max Power System" operation.*

Relative to standard liquid cooling (LC), the 2-PC approach demonstrated improved cell voltage homogeneity. A marginal performance penalty (<1%) at maximum power was identified. As expected, a strong reduction in parasitic pump power (-78%) due to a lower coolant mass flow was achieved. Furthermore, the system proved stable under high subcooling conditions (>15K), supporting mechanical pump compatibility. The results establish a solid foundation for the continued development and scaling of a 2-PC FC system architecture for commercial aviation.

Acknowledgement: Funded by the European Union's Horizon program under grant agreement number 101101409. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the granting authority "Clean Hydrogen Joint Undertaking". Neither the European Union nor the granting authority can be held responsible for them.

Aerodynamic Design and Evaluation of Open and Shrouded Propellers for eVTOL Applications

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1. Introduction / Objectives

Electrification of aircraft propulsion systems is a key component of future low-emission and especially locally quiet air transport concepts. Electric propulsion offers particular advantages for eVTOL aircraft in the short-haul segment due to their high efficiency and the potential for close functional system integration. At the same time, new challenges arise regarding vehicle design, off-design behavior, structural dynamics and thermal constraints.

In PEANUT, design studies for an eVTOL concept were conducted to determine appropriate reference aircraft concepts and define propulsion performance requirements on this basis. The propeller was designed as an open rotor for the full-scale version while a scaled propeller was designed and manufactured for scaled wind tunnel tests in both open and shrouded aerodynamics. Wind tunnel tests and wake measurements were conducted for axial and inclined flow of both configurations with their results providing a basis for optimizing the combined shroud to propeller aerodynamics.

2. Methodology

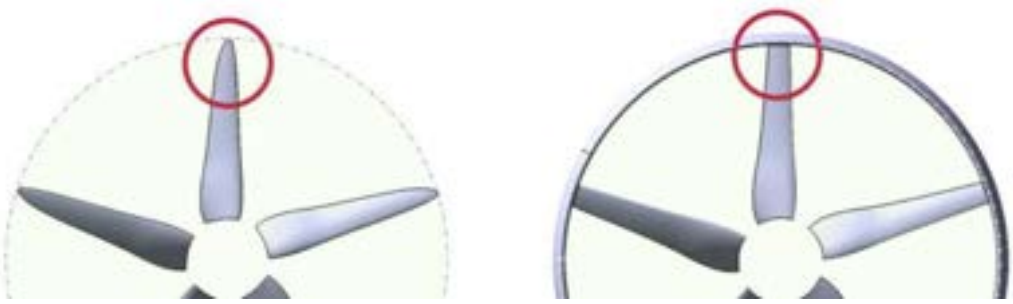


Figure 1. *Schematic downstream view of the investigated propeller designs, conventional un-shrouded five-bladed propeller (left) and shrouded propeller design including duct (right).*

The initial reference aircraft design was based on OAD methods. The target mission profile was for four passengers (including pilot), a corresponding payload of 400 kg along a range of 100 km at a cruising speed of 240 km/h. The profile included segments for the takeoff hover phase, the "multi-copter" climb phase (lift provided exclusively by the rotors), the accelerated "fixed-wing" climb phase (lift provided exclusively by the wings), and the cruise flight. The descent phase was defined using "fixed-wing" and "multi-copter" phases as during the climb phase respectively. To assess the eVTOL performance of for the required mission, eight different configurations (P1 through P8) were designed, each with a total of six to twelve propellers. Some of these concepts combine tiltrotors with additional lift rotors. Configurations with a smaller number of rotors were not considered for flight safety reasons. Dimensioning of the power electronics as well as the battery pack was also done using preliminary design methods for both disciplines based on power density reduced order modelling. Special effort and medium-fidelity methods were used to model the cooling system for power electronics and electric motors in steady state as well as in transient operation. This allowed coupling to aero-thermodynamic cooling modelling using different areas of the propeller shroud surface for

cooling analysis in order to focus on the critical aspect of coolant-to-air heat transfer. For the propeller design an extended blade element momentum theory (BEMT) in combination with the process described by Adkins and Liebeck was used. To limit the aero-acoustic noise generation, the propeller tip speed was limited to Ma_{Tip} = 0,4 leading to 1250rpm design speed at a diameter of 2,05m. As aerodynamic design point, the hover part of the mission was chosen and the blades were design based on mh116 and mh14 profiles. For the shrouded propeller the shroud profile was designed based on a modified NACA-0012-profile with flattened pressure side to generate a cylindrical inner contour. The leading edge of the shroud was design was the tip radius of the un-shrouded propeller, leading to a propeller tip radius of 97% of the un-shrouded blades, see also Fig. 1.



Figure 2. *Open wind tunnel setup for shrouded propeller mounted on turntable for non-axial flow condition experiments).*



3. Results / Conclusions

The selected eVTOL concept with the lowest energy demand consists of 12 identical propellers of which six are operated as tilt systems while the other six are lift-only systems. For the location of waste heat transfer areas at the outer shroud surface, positions between 15 and 60% along chord appeared feasible up the to position of outer stagnation point during hover, while all positions closer to the shrouds leading edge area showed a negative impact. Comparing both propellers the typical thrust augmentation for low advance ratios was found for the shrouded version. The thrust gain was in the typical margin known from other shrouded designs. However – as it will be discussed in the full paper, the pressure distribution along the duct showed potential for even higher thrust augmentation. In parallel, the shrouded system showed a more sensitive AoA behavior combined with a distinct downstream flow characteristic (cf. Fig. 3).

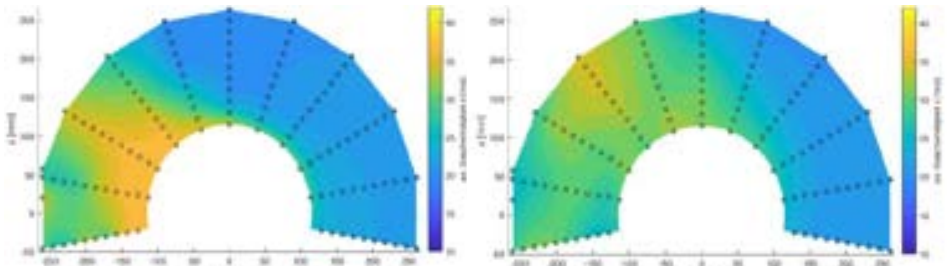


Figure 3. *Downstream velocity distribution (approx. 1,5D behind propeller) at 25 m/s. Open propeller (left side) shrouded propeller (right side).*

Comparison of numerical and experimental investigations of an air cooling duct under propeller slipstream, crosswind, and headwind effects

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1. Introduction / Objectives

The aerodynamic performance of cooling ducts integrating tilted heat exchangers (HEX) varies significantly under the influence of dynamic flight conditions. Factors such as propeller slipstream, crosswinds, and headwinds induce unsteady, heavily distorted flow regimes within the duct thereby significantly compromising system efficiency. This study presents a comparison between high-fidelity computational fluid dynamics simulations and 1:6 scaled wind tunnel experiments to evaluate the performance of air-cooling ducts with an integrated tilted HEX. The approach uses a sequential numerical workflow bridging external and internal aerodynamics for a more rigorous analysis and is developed within the Clean Aviation Joint Undertaking project FAME (Fuel Cell Propulsion System for Aircraft Megawatt Engines).

2. Methodology

Reynolds-Averaged Navier-Stokes (RANS) simulations are used to resolve the external flow field under flight conditions, from which the inlet mean flow with turbulence parameters are extracted and applied as inlet boundary conditions into high-fidelity Large Eddy Simulations (LES) of the internal aerodynamics. Inside the duct, the HEX is modeled via a Darcy-Forchheimer porous media approach utilizing a self-adapted version of transient OpenFOAM solver, pisoTempFoam , to capture coupled momentum and heat transfer. The investigation specifically considers the non-uniform, highly distorted flow topology immediately upstream of the HEX, where accurate inlet boundary conditions and curvature-induced flow separation are most critical.

3. Results / Conclusions

The pressure losses, flow distortion, and overall performance under dynamic flight conditions are shown to be well predicted by cross-validating the LES predictions against experimental measurements. The results of experiment and numerics are compared under simulated flight conditions, including variations of propeller slipstream, crosswind, and headwind. Thus, the validated methodology provides a robust predictive foundation for optimizing internal duct performance and mitigating duct-induced losses for a complex aircraft propulsion architecture.

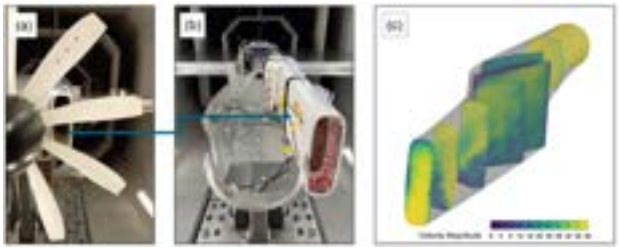


Figure 1. (a) *and* ***(b)*** *Experimental wind tunnel setup, and* ***(c)*** *instantaneous velocity iso-surfaces from a 3D LES simulation under propeller on & head wind configuration.*

Acknowledgement: The author acknowledges the funding of the project FAME by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

Modeling of Coupled Bearing Chamber and Scavenge Line Processes in a Gas Turbine Engine

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1. Introduction / Objectives

The operation and reliability of gas turbine engines largely depend on the performance of the lubrication system, which provides lubrication and cooling of bearing chamber components. In gas turbine engine bearing chambers, a complex air-oil two-phase flow develops due to the interaction between sealing air and lubricating oil used for friction unit lubrication and cooling. Efficient operation of the lubrication system is essential for maintaining thermal stability and operational reliability of bearing chambers. The interaction between the bearing chamber and the scavenge line significantly affects oil accumulation, air entrainment, heat transfer, and pressure stability. However, existing studies typically consider these subsystems separately, while their coupled thermohydraulic behavior remains insufficiently understood.

The objective of the present work is to develop a coupled model of the bearing chamber and scavenge system for simulation of air-oil processes in gas turbine engine lubrication systems, supporting their preliminary design and optimization.

2. Methodology

The air-oil flow in a gas turbine engine bearing chamber (Fig. 1) is formed due to the interaction between sealing air and lubricating oil supplied for lubrication and cooling of friction units. The complex flow behavior is determined not only by the bearing chamber geometry, but also by the presence of rotating elements, oil supply configuration, and flow scavenging conditions.

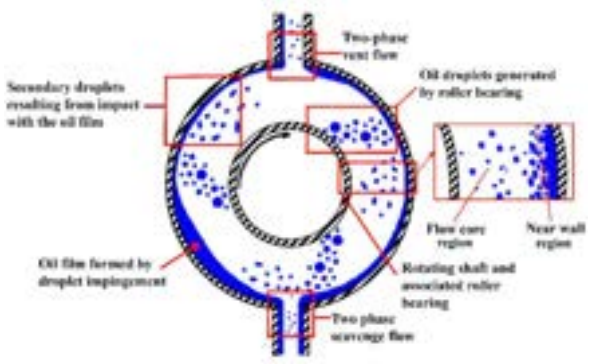


Figure 1. *Multiphase flow structure in the bearing chamber*

The large number of influencing factors complicates the development of a comprehensive mathematical model of the processes occurring in the bearing chamber and scavenge line. As a result, different modeling approaches are typically employed: three-dimensional computational fluid dynamics (CFD) simulation of heterogeneous air-oil flow is commonly used for bearing chamber analysis, while one-dimensional multiphase flow models are applied to scavenge lines. Such approaches require significant computational resources and increase simulation time. In addition, difficulties associated with the specification of initial and boundary conditions limit their applicability at the preliminary design stage of bearing chambers and lubrication systems.

The developed approach combines mass, momentum, and energy conservation equations with semi-empirical correlations for two-phase flow. The model accounts for the dynamic interaction between air and oil flows in the bearing chamber, as well as the hydraulic characteristics of the scavenge system.

The approach is based on describing multiphase flow processes in the bearing chamber using validated equations of heterogeneous medium mechanics with reduction to a two-dimensional formulation through axial averaging of phase parameters . Due to the low volumetric concentration of droplets, a Lagrangian approach is employed for modeling two-phase flow in the chamber core. Droplet trajectories are calculated taking into account interaction with the air flow, whose velocity field is determined by chamber geometry, sealing air flow rate, and shaft rotational speed. The approach makes it possible to consider droplet polydispersity, rebound, secondary droplet formation, and wall oil film development, whose thermal resistance affects the heat transfer coefficient.

Particular attention is devoted to the influence of scavenge line hydraulic characteristics on bearing chamber operation. The effects of hydraulic resistance, air entrainment, and operating conditions on oil accumulation and the chamber thermal state are investigated.

3. Results / Conclusions

An integrated two-dimensional flow model of the gas turbine engine bearing chamber and scavenge line is proposed as an alternative to three-dimensional CFD simulations, which require significant computational resources. This model can be used for preliminary design of gas turbine engine lubrication systems.

A parametric study was performed using the developed model to investigate the influence of key parameters on heat transfer and fluid flow in the bearing chamber. These parameters include shaft rotational speed, air and oil mass flow rates and temperatures, as well as bearing chamber pressure and scavenge line characteristics.

The results show that scavenge line characteristics significantly affect thermohydraulic processes in the bearing chamber. In particular, under certain conditions, an increase in scavenge pump capacity may lead to flow blockage in the scavenge line, causing an imbalance between oil supply and scavenging, and increasing the risk of bearing overheating and oil leakage into the gas path.

CFD-Analysis of an integrated Turbofan Guide Vane Heat Exchanger for Hydrogen and Conventional Propulsion systems

Gernot Burghard Hedjri-Peyfuss, Patrick Laggner, Helmut Mad
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1. Introduction / Objectives

Modern turbofan engines achieve high efficiency through high bypass ratios. In terms of further performance improvements, this work investigates the integration of an oil–air heat exchanger into bypass guide vanes, utilizing waste heat from gearbox oil to increase thrust by heating the secondary flow, analogous to the Junkers–Meredith effect. In relation to conventional designs, this concept introduces a multifunctional component, combining aerodynamic, structural, and thermal functionality.
Hollow guide vanes with internal oil channels are required for implementation. The study simulates different heat exchanger types and analyzes how the number and arrangement of internal channels affect heat transfer performance. Furthermore, the resulting thrust increase is predicted by means of calculations, enabling an beneficial assessment of the overall performance increase. These simulation results provide new insights into coupled flow and heat transfer by internally cooled turbomachinery components under operational conditions.

2. Methodology

The methodology combines parametric geometry modeling, numerical simulation, and comparative CFD analysis to evaluate an integrated guide vane heat exchanger concept. A baseline guide vane geometry was adapted to a hollow structure with integrated oil channels while the external aerodynamic profile was kept as unaffected. Multiple design variants were generated by systematically varying the number and arrangement of internal channels to represent different heat exchanger configurations.
To reduce the needed computational resources as first step, only a periodic segment of a single guide vane and the surrounding bypass flow was modeled. The computational domain was divided into three coupled regions: external airflow, solid vane material, and internal oil flow, enabling a conjugate heat transfer analysis.
The simulations were conducted using a finite-volume CFD solver (Simerics MP+) . Unstructured meshes were generated for all domains, with local refinement near the vane walls and internal channels to accurately resolve thermal boundary layers and heat transfer between oil, solid, and air.
A steady-state approach was applied, and turbulence effects were modeled using the Renormalization Group (RNG) k–ε model to capture complex flow structures. Boundary conditions were defined to represent realistic operating conditions, including a swirling inflow profile for the bypass air, fixed pressure at the outlet, and prescribed oil inlet temperature, velocity, and pressure conditions.
In the second step different heat exchanger configurations were compared by evaluating heat transfer rates and temperature distributions, allowing a systematic assessment of the influence of internal channel design on thermal performance.
Finally, the potential increase in thrust due to the Junker-Meredith effect is calculated on the basis of the transferable thermal power.

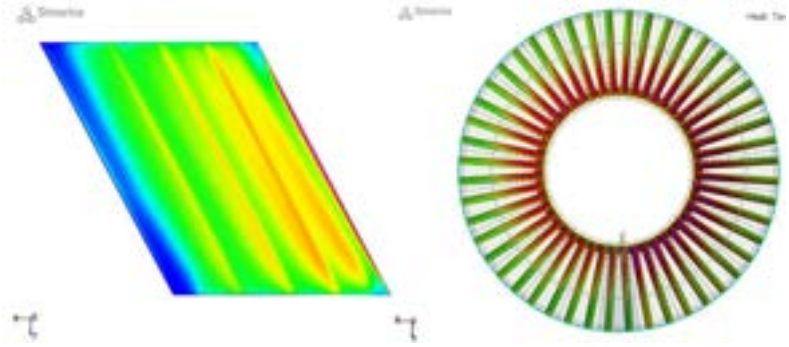


Figure 1. *Periodic segment of the guide vane (left), Serial configuration (right)*

3. Results / Conclusions

The results confirm the technical feasibility of integrating an oil–air heat exchanger into bypass guide vanes for simultaneous thermal management and performance enhancement. An increase in the number of internal oil channels leads to a higher overall heat transfer rate, indicating that enlarged internal surface areas improve thermal effectiveness.

A significant reduction in oil temperature is achieved under standard operating conditions, demonstrating sufficient cooling capability within allowable limits. However, the results reveal non-uniform heat transfer distributions along the radial direction and indicate potential performance limitations under elevated ambient temperatures.

Overall, the approach represents a promising pathway for enhancing turbomachinery efficiency through the combined utilization of waste heat and aerodynamic components, although further optimization and validation under realistic operating conditions remain necessary.

Furthermore, the concept is also considered applicable to hydrogen-based propulsion systems, where efficient thermal management is of increasing importance.

Water droplet spray injection for optimization of RAM air heat exchangers in next-generation aircraft: proof of concept, test set-up and results

Monique Lamers, Thomas Ganzeboom, Johannes van Es
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1. Introduction / Objectives

Current developments in next-generation aircraft lead to new thermal challenges. This research explores the concept of injecting water droplets into the airflow to improve the performance of a RAM air heat exchanger. Heat exchangers are sized for take-off, where peak heat loads occur and airflow is minimal. An improved heat exchanger allows for smaller designs, which can be achieved by pre-cooling the airflow. This research explores the effect of water droplet addition to an airflow and the possible advantage for heat exchanger performance. A droplet cooling model is developed for simulations. The simulations are then verified by experiments.

2. Methodology

The droplet cooling model calculates the air and water properties and heat transfers in the airflow. The droplet cooling is modelled by describing the evaporation process of the water droplets. The evaporation process is based on diffusion of water from the droplet's surface into the air. The simulations' results are compared to experimental results. The test set-up consists of a condition simulator, spray section and evaporation section. The condition simulator creates an airflow at the desired speed, temperature and relative humidity. Three conditions are explored: a laboratory, a warm and humid, and a hot and dry environment. The spray section introduces a g/s water spray created by several spray nozzles into the airflow. The sprayed airflow enters the evaporation section, which is equipped with thermocouples, where the droplets mix with the flow and evaporate. The verification of the modelled evaporation process is done by comparing the temperature profiles over the test set-up's length.

3. Results / Conclusions

The simulations show promising results, as the spray introduces an immediate temperature drop of the airflow. The temperature stays approximately constant in the simulations. However, the experiments show a gradual increase due to heat transfers with the test set-up and environment. The temperature profiles of the expected and measured airflow are comparable, although less pronounced. Nonetheless, the temperature of the test set-up is generally lower than the conditioned temperature. Therefore, the results confirm the expected cooling effect of evaporating small water droplets in an airflow.

Gradient-Based Aerodynamic Optimization and Experimental Validation of a Wing-Integrated Heat Exchanger for Fuel Cell Aircraft

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Technische Universität Dresden, Germany

1. Introduction / Objectives

The electrification of aircraft propulsion through fuel cell systems introduces significant thermal management challenges. Proton exchange membrane fuel cells generate substantial waste heat at relatively low temperatures, and its dissipation via ducted radiators incurs aerodynamic drag penalties comparable to those of conventional engine nacelles . Wing-integrated heat exchangers offer a promising alternative by exploiting the pressure differential between the airfoil's suction and pressure sides to drive cooling airflow through an internal radiator, while avoiding additional external structures and their associated drag. This study investigates the aerodynamic characteristics of wing-integrated heat exchangers through a combined numerical and experimental approach. The primary objectives are: (i) to identify favorable airfoil and channel geometries using gradient-based shape optimization, (ii) to validate the numerical findings through wind tunnel experiments, and (iii) to assess the influence of heat addition on aerodynamic performance. The reference application is a hydrogen-powered general aviation aircraft.

2. Methodology

A two-dimensional CFD simulation framework was established in ANSYS Fluent using a pressure-based solver with the SST k-ω turbulence model. The heat exchanger was represented by a porous media zone characterized by its inertial resistance factor C_2, enabling the investigation of various radiator pressure loss characteristics without requiring specific internal geometries . Four airfoil candidates (Eppler 403, FX 73-170, NACA 4415, NACA 43012A) were modified with an internal channel connecting the pressure and suction sides.

A gradient-based optimization was employed to maximize a custom objective function combining heat transfer strength (based on radiator volume and flow velocity) and aerodynamic efficiency (lift-to-drag ratio). This approach exploits sensitivity information to guide shape modifications across the entire airfoil geometry, overcoming limitations of parametric studies regarding the high-dimensional design space . Inertial resistance factors between 3 and 160 m^{-1} were investigated. The actual heat transfer performance was evaluated post-optimization using the NTU method for a finned-tube cross-flow heat exchanger.

Based on the optimization results, the NACA 43012A variant with C_2 = 20 m^{-1} was selected and manufactured as a wind tunnel model (chord = 0.6 m, span = 1.2 m). The model features interchangeable 3D-printed perforated sheets simulating pressure loss coefficients between $\zeta \approx 3$ and $\zeta \approx 7$, as well as an integrated aluminium heat sink with heating foils (300 W total) to assess the influence of heat addition. The lift coefficient is derived from static pressure measurements along the airfoil surface, while drag is determined from momentum-deficit measurements using a wake rake. Wind tunnel tests were conducted at TU Dresden's closed-return open-jet facility at velocities of 20–40 m/s (Re ≈ 820,000–1,640,000).

A three-dimensional validation simulation (≈20 million cells) incorporating the SST k-ω model with intermittency transition was created, replicating the exact wind tunnel geometry including heat sinks and perforated sheets, to obtain quantities not directly measurable (e.g., channel pressure loss) and validate the numerical findings.

3. Results / Conclusions

The gradient-based optimization demonstrated that careful harmonization of wing and channel geometry can increase the heat flow rate by a factor of two to three while maintaining comparable lift-to-drag ratios (L/D ≈ 25–30 at design conditions). Figure 1 shows such an optimized configuration alongside the unmodified reference airfoil. Wind tunnel measurements showed satisfactory agreement with the validation simulation for pressure distributions and aerodynamic coefficients.

Testing across multiple pressure loss configurations revealed that increasing the radiator pressure loss, and thus heat transfer, does not necessarily compromise aerodynamic performance, confirming the importance of treating radiator and airfoil as a coupled design problem. Heated-flow experiments indicated a slight drag increase without measurable changes in lift or pressure distribution. An unusual decrease in maximum lift coefficient with increasing Reynolds number warrants further investigation.

These findings support wing-integrated heat exchangers as a viable low-drag thermal management solution for next-generation fuel cell aircraft.

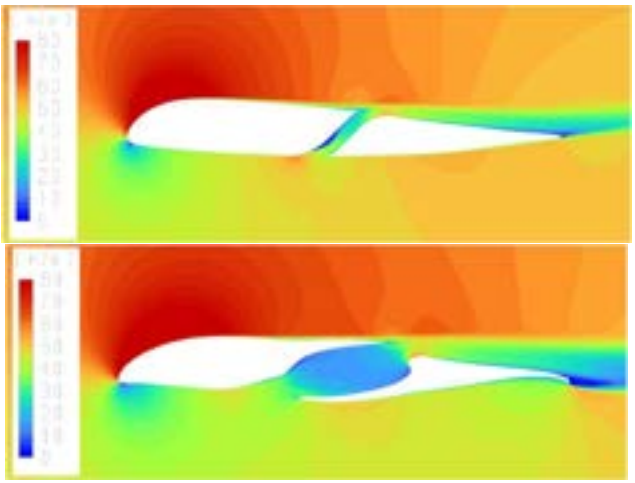


Figure 1. *Velocity magnitude contours of the NACA 43012A airfoil with unoptimized channel geometry (left) and after gradient-based optimization with $C_2 = 20\ m^{-1}$ (right), showing the inlet on the pressure side and outlet on the suction side.*

Design and testing of a 65 kW Two-Phase Mechanically Pumped Loop Demonstrator for Aerospace Power Electronics Cooling

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[2] Liebherr-Aerospace Toulouse, France

[3] Affiliation and country not provided

1. Introduction / Objectives

The transition from conventional propulsion systems to hybrid electric propulsion systems for small-to-medium range aircraft is technically challenging. One of the challenges is the large amount of heat generated by the electric systems. In conventional aircraft a small amount of heat is generated at elevated temperatures. This heat is rejected to the outside air by a small air heat exchanger. The new hybrid architectures dissipate an order of magnitude more heat at a lower temperature. Fuel cells operate around 95 °C, whereas the power electronics may even be as low as 30 °C. This requires much larger cooling systems, and hence their relative weight increases. Two-phase cooling systems are generally more lightweight than liquid glycol-water cooling systems. Liquid cooling systems are however still the standard in conventional aircraft. This research focusses on the applicability of new

lightweight two-phase mechanically pumped cooling systems (2F-MPL) and demonstrate their benefits.



Figure 1 - Picture of the two-phase MPL and the Battery simulator.

2. Methodology

In the Thema4HERA project a flexible two-phase mechanically pumped loop (2F-MPL) cooling system has been developed, build and tested (see **Error! Reference source not found.**). The 2F-MPL cools multiple heat loads in parallel ranging from 2 kW to 34 kW. In cruise conditions a total of 65 kW heat can be collected and transported to a direct RAM air HX to dissipate the heat to the environment. In hot take-off, climb and go-around cases the 2F-MPL can be connected via a VCS to the RAM air HX to elevate the heat above the high ambient temperatures.

As additional design margin, the thermal mass of the whole system, including the battery, may be used to overcome a short duration in which the VCS cooling capacity at the RAM air HX is not sufficient, e.g., during hot take-off. Therefore, care is taken to make the heat loads representable for (future) applications. One heat load of interest is the battery. The battery has a particularly high thermal mass due to its size. Aside from the battery there is a heat load with a high heat flux (> 45 W/m2) representative for future power electronics, a heat load with a heat flux representative for batteries and two additional heat loads representing state-of-the-art power electronics. The last heat load is hot air from the fuel cell compressor collected by a 2-phase MPL-air heat exchanger. Due to the simplicity of the system the design was found to be very flexible to design changes such as extra payloads or changes in dissipation. This aids the integration of this type of system on the platform. Since two-phase MPLs generally have a high COP (>500), pump power is not a design driver, and the rotational speed of the pump is kept constant to even further simplify the control.

The two-phase MPL is designed, build and tested by the NLR, whereas the connected VCS is designed, build and tested by LTS. This paper discusses the benefits and design methodology for the 2F-MPL. Test results for the isolated 2F-MPL are presented and discussed including unbalanced heat load tests, battery thermal mass tests and take-off simulations. It is expected that also the first 2F-MPL-VCS operations will be presented.

3. Results / Conclusions

The two-phase MPL is build and tested. The test data showed that the cooling performance was in line with expectations. The system can cool multiple payloads in parallel also when heat loads vary much over time or per payload. Preliminary results indicate that the thermal mass of the combined systems can temporary increase the cooling capacity when the cooling capacity to ambient air is limited due to environmental hot take-off conditions.

Gaseus and Liquid Hydrogen storage and refuelling for aviation

Chaired by:
Mr. Georgios Bampanis (European Climate, Infrastructure and Environment Executive Agency – CINEA)

High-Flow Liquid Hydrogen (LH2) Refuelling for Aviation: Preliminary Results and Technical Developments from the GOLIAT Project

Jean-Christophe HOGUET[1], Peter CALVERT[1], Lukas Steiger[2], David Ascic[2]
[1] Airbus, France
[2] Chart Industries, United States

1.Introduction / Objectives

Decarbonising the aviation sector, particularly for short- and medium-haul flights, requires the adoption of hydrogen as a sustainable energy carrier. However, the transition to hydrogen-powered aircraft necessitates a mature supply infrastructure and efficient daily airport ground operations. The GOLIAT (Ground Operations of LIquid hydrogen AircrafT) project, funded by the European Union, aims to overcome current technological, regulatory, and economic obstacles to enable the widespread use of liquid hydrogen (LH2) at airports. A critical challenge is the development of high-flow refuelling technologies that can meet airline requirements for turnaround times and operational costs.
This paper presents the intermediate results of the GOLIAT project, focusing on the design and development of high-flow LH2 refuelling systems. The primary objective is to demonstrate the feasibility of refuelling rates compatible with commercial aviation needs through the development of both ground-based and aircraft-based prototypes.

2.Methodology

The research follows an integrated approach across several work packages. A ground-based mobile LH2 refueller prototype is being designed and manufactured, featuring a two-unit configuration (a trailer for the tank and pump, and a separate platform for the balance of equipment). Simultaneously, a representative aircraft-based LH2 fuelling system, including a 400kg LH2 capacity tank and a specialized refuel coupling, is under development. The methodology includes rigorous safety studies, preliminary hazard identification (HAZID), and the preparation of integrated tests at the Airbus Zero Emissions Development Centre (ZEDC) in Filton, UK.

3.Results / Conclusions

Intermediate results have established a target flow rate for the refueller prototype

between 5 and 7.2 tons per hour. A comprehensive feasibility study (D5.1) completed in April 2025 has given clues for the LH2 refuelling infrastructure at European airports to be technically feasible. Furthermore, initial work on standardization and certification has identified key gaps in unified rules for mobile LH2 operations, emphasizing the need for airport-specific regulatory compliance strategies and specialized training. Detailed engineering for the refuelling system is progressing according to schedule, with the testing phase expected in Q3/Q4 2027.
The preliminary findings from GOLIAT demonstrate significant progress in mastering high-flow LH2 refuelling technologies. The defined target flow rates refuelling sequences definition lay the groundwork for the next phase of integrated demonstrations. These developments are essential to ensure that LH2 ground operations are safe, efficient, and economically viable for the future of climate-neutral aviation.

Acknowledgement: This research is sponsored by the GOLIAT project funded by the European Union (Horizon Europe) with grant agreement nr. 101138379.

An Assessment of Turnaround Time, Logistic and Safety Distances for LH2 refuelling in Airport

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1. Introduction / Objectives

The introduction of future hydrogen-powered aircraft (HPA) and hybrid electrical regional aircraft (HER) need to consider safe and time-efficient servicing at airports, particularly when liquid hydrogen (LH2) is used. So far, no precise regulatory framework or operational protocol exists for refuelling and associated ground operations at airports.
This work consists of: 1) a study on the ground operations for servicing a future zero emission regional aircraft (ZERA), to estimate its turnaround time and the logistic of ground operation, including refuelling; 2) an estimation of the safety distances to observe during LH2 refuelling. The outcomes of the work, performed within the project ALRIGH2T, are applied to a planned demonstration of LH2 refuelling in Milan Malpensa. The objective is to support the preparation of the demonstration, the authorisation process, the establishment of rigorous safety protocols and the acquisition of technological and operational know-how, also through the use of a virtual reality (VR) training ecosystem.

2. Methodology

The work preliminary defines the LH2 fuelling-defueling procedure for a future ZERA ("CS25-100 passengers" class), as expected first relevant application of HER and, later on, HPA . The logistic study starts from current fuelling operational practices (for Jet-A1) at airports, which

are then analysed and tailored for the future ZERA. The ground vehicles required for aircraft servicing and refuelling, the positioning on an airport stand, the sequence of operations and their durations are defined. These include arrival, cargo offloading and loading, water service, refuelling, passengers deboarding and boarding. Where possible, concurring activities are scheduled to minimise turnaround time. The LH2 refuelling is the most critical operation, estimated using the procedure in alongside realistic technology assumptions.
The calculation of the safety distances from LH2 transfer points follows the most up-to-date industry standards, which are converging on risk-informed, scientific approache . Three "Exposure Groups" are used, based on different heat fluxes and overpressure in case of fire or explosion of LH2: 1) *Off-site and public protection*, 2) *On-site Personnel Protection*, 3) *Asset/Property Protection*. The first (the most conservative), dictates the exclusion safety area, accessible only to essential, trained personnel with certified equipment. It corresponds to the reachable distance of flammable vapor cloud, calculated with the mass flow through the refuelling nozzle and the pressure of the fuel transfer system. A second safety zone (Apron Management zone) is established for managing general apron activities, providing a buffer for emergency response and mitigating the hazard of Groups 2 and 3. LH2-delivering Trucks are considered part of the transfer systems; thus their connection points are subjected to the same zoning.
Lastly, the layout, the logistic and the calculations performed are downscaled to fit the ALRIGH2T demonstrator, which uses a real scale (1:1) mock-up of a Piaggio P180 with a 50 kg LH2 tank installed onboard. These are integrated into a VR framework that replicates the exact spatial configurations of the hardware used, leveraging high-precision aerial LiDAR scans and airport vector datasets to create a precise virtual model for training ground crew.

3. Results / Conclusions

The operation analysis for a regional aircraft finds out that the minimum turnaround time is ~40 minutes. The key time-limiting factor is the actual refuelling, which depends on the refuelling technology and the fuel capacity of the aircraft. Furthermore, no other operation is expected to be performed during the refuelling for safety reasons. The sequence and the length of operation is expected to be similar for the scaled-down physical demonstration; the refuelling time reduces to 6-8 minutes. The safety assessment identifies the following safety radii for a 2" (51 mm) nozzle diameter and 5.5 bar: 7 m for couplings between LH2 delivery elements; 14 m for the exclusion zone (protection from ignition); 30 m for the apron management zone. Figure 1 illustrates the layout for the refuelling of a ZERA. These results will be exploited in the authorisation, organisation and execution of the physical demonstration, while also increasing the know-how bodywork of LH2 for aviation.

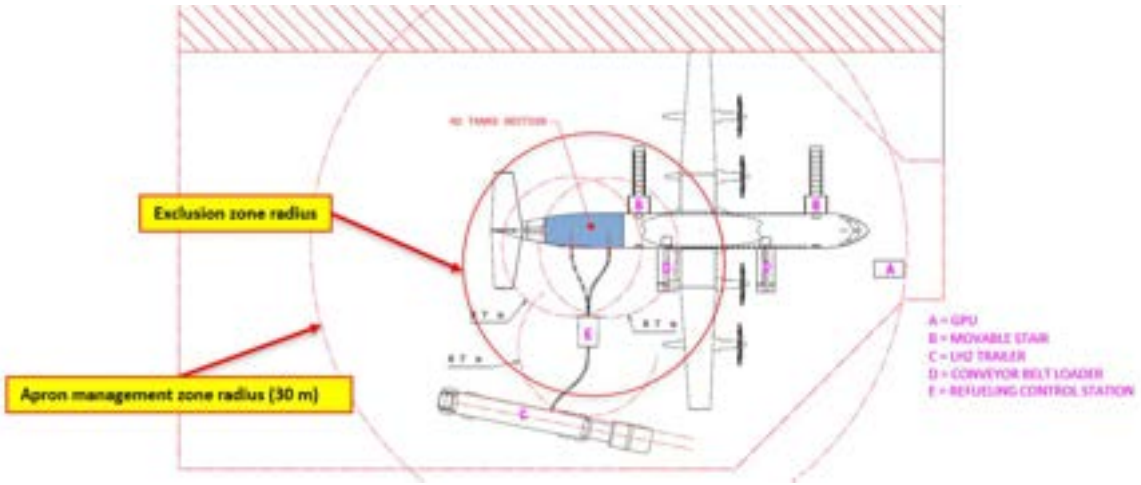


Figure 1. *Refuelling layout for a ZERA*

Acknowledgement: The present study was conducted within the Horizon Europe project ALRIGH2T (Grant Agreement no. 101138105), funded by the European Union.

Modeling and Optimization of Airport LH_2 Dispensing Unit Fleets

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1. Introduction & Objectives

Aviation sector is responsible for 3% of global CO_2 emissions, a share projected to increase to 25% in the coming decades . Decarbonizing this sector is therefore a critical challenge. While Sustainable Aviation Fuels (SAF) represent a near-term solution, liquid hydrogen (LH_2) is emerging as a key vector for long-term decarbonization, with forecasts suggesting that 6% of flights could be operated by hydrogen-powered aircraft by 2050 . Such a transition requires airports to fundamentally adapt their ground infrastructure and operations to handle LH_2 safely and cost efficiently. This study investigates the LH_2 distribution to aircraft using LH_2 refuelling trucks. The numerical model determines the optimal fleet size of LH_2 trucks for a given period, calculates required LH_2 quantities, and generates truck scheduling while accounting for spatial constraints within the airport. This study will focus on Lyon–Saint Exupéry Airport, an airport of the VINCI Airports network.

2. Methodology

The model under development is designed to support airport needs for the 2050 horizon, considering the introduction of hydrogen-powered aircrafts. It focuses on the use of LH_2 refueling trucks, easiest starting option for hydrogen aircraft refueling , developed by CHART Industries as part of the GOLIAT project, co-developed by Airbus and co funded by the European Commission . The numerical model is coupled with an optimization strategy to determine the minimal number of LH_2 refueling trucks required for ensuring the airport operations. The airport data used by the model, such as flight schedules (arrival and

departure times, destinations), airport layout, and potential locations for LH_2 refueling truck parking and entry points, are provided by Lyon Saint-Exupéry Airport (AdL). Technical specifications for the refueling trucks and aircraft characteristics are provided by the GOLIAT consortium, which includes AdL and VINCI. Various parameters are progressively included into the model to increase its physical relevance: Boil Off (hydrogen losses due to evaporation) within the refueling trucks and aircraft tanks, detailed sequencing of the ground operations during the aircraft turnaround. Data from the GOLIAT project are used to determine the possibility of parallel operations and the associated time of operation.



Figure 1. *Simulations of an LH_2 refuelling truck trajectory at Lyon Saint-Exupéry Airport.*

The model also exploits a study conducted by AdL for the GOLIAT project, which determines safety distances within the airport and relevant paths of the LH_2 refueling trucks. In Figure 1, the typical path of a LH_2 refueling truck developed in the GOLIAT project at AdL is illustrated for the refueling of a single aircraft. The model incorporates the results of this study to determine the distance from the entry point to the aircraft parking stand and compute the corresponding time required to travel from one point to another. The various modules forming the full model are developed using MATLAB and several optimization strategies are currently investigated to achieve a computationally efficient determination of the minimal-cost LH_2 refueling strategy.

3. Preliminary Results

Using the required liquid hydrogen quantity for each flight and the refuelling duration based on the LH_2 refuelling trucks or dispensing units (DUs) technical specifications, an optimal refuelling strategy is computed which ensures the flight schedule is satisfied while the required fleet of DUs is kept to a minimal size – cost minimization in this preliminary stage. The model outputs key information for an airport such as the average DU utilization and the peak number of units deployed during a given period. To validate its performance, a simple sanity check is conducted with 47 flights featuring a significant traffic peak around hour 15.

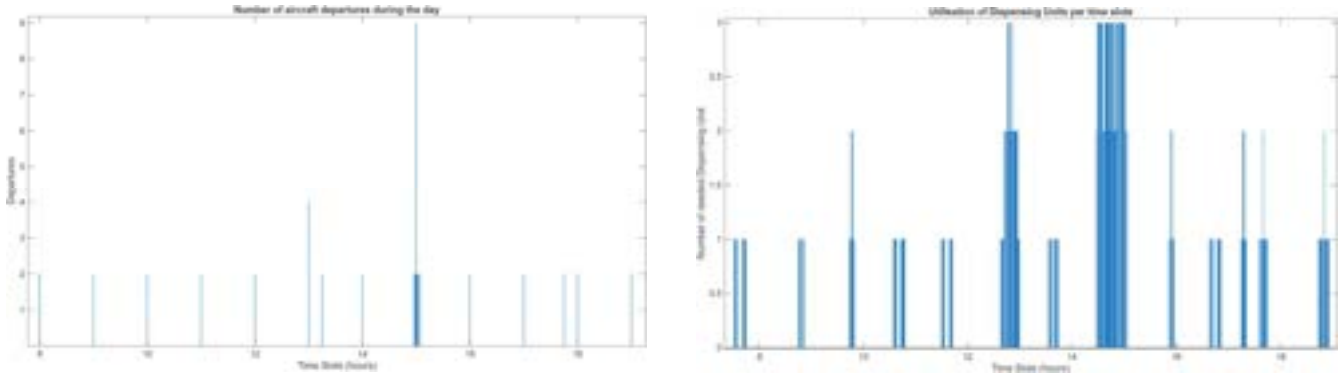


Figure 2. *Charts of the number of departures (left) and dispensing units (right) during a day of operation.*

As shown in Figure 2, during peak demand around the hour 15, 9 flights are serviced using only 3 DUs. This result illustrates the model's ability to optimize resource allocation. The analysis presented at the Conference will consider a realistic description of the AdL operating with a hydrogen-powered aircraft and ground service equipment fleet.

LH_2 supply-cost uncertainty for H_2-powered aviation: European airport case studies

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1. Introduction / Objectives

Liquid hydrogen (LH_2) is considered one promising fuel option for achieving net-zero aviation, but its implementation requires substantial investments in dedicated hydrogen (H_2) supply infrastructure . These infrastructure decisions must be made under deep uncertainty regarding future H_2-aircraft demand uptake, renewable energy availability, technology readiness levels and H_2-market development. This results in a first-mover problem for airport stakeholders and infrastructure operators. Previous studies have mainly focused on deterministic scenario-based techno-economic analyses of LH_2 supply costs and supply pathways. The main objective of this study is to quantify a uncertainty range for airport-specific LH_2 supply costs and infrastructure requirements. The technological and scientific innovation lies in linking a mixed-integer linear optimization model (MILP) for LH_2 airport supply chains with probabilistic parameter sampling to derive cost distributions and infrastructure implications for H_2-powered aviation.

2. Methodology

A Monte Carlo-based techno-economic assessment is applied to airport case studies. The investigated time horizon covers the period from 2035 to 2055. The selected airport case

studies represent different airport archetypes in terms of size, location, renewable energy availability and H_2 infrastructure readiness as illustrated in Figure 1. In addition, a dedicated cluster case is investigated, in which selected infrastructure components are jointly sized for the combined H_2 demand of two airports. Airport hydrogen demand is represented using hourly demand profiles and long-term demand ramp-up trajectories. A techno-economic optimization model for LH_2 supply chains for airports is used, based on Schenke et al. . The objective function minimizes total annualized LH_2 supply costs. The model represents the main components required to supply LH_2 for aviation, including renewable energy generation, electrolysis, liquefaction and storage, as well as the transport of gaseous and liquid H_2.

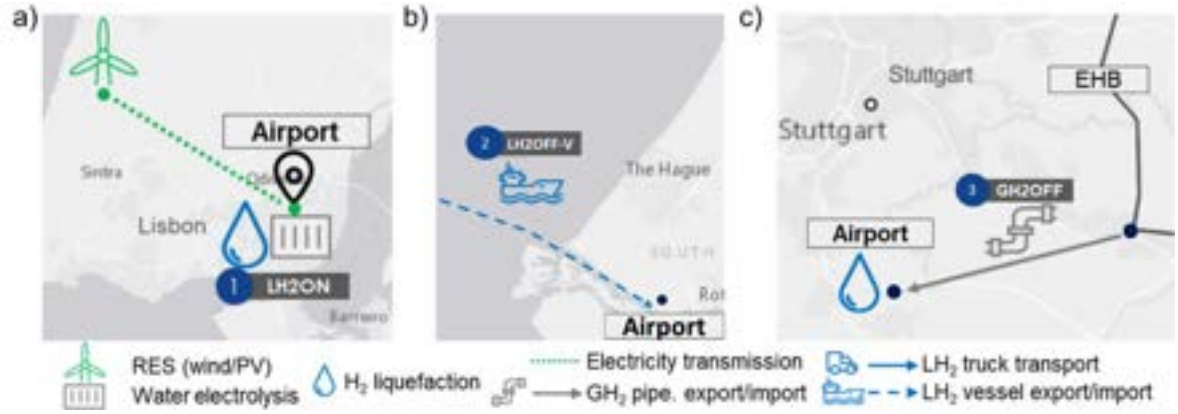


Figure 1. *LH_2 supply pathways for the investigated airport case studies: a) Lisbon Airport with on-site LH_2 production, b) Rotterdam The Hague Airport with off-site LH_2 production and vessel transport, and c) Stuttgart Airport with off-site GH_2 production and pipeline transport*

Uncertain techno-economic parameters are represented through probabilistic input distributions. Monte Carlo sampling is used to generate a large number of internally consistent techno-economic input sets for selected years. For each sample, the MILP model is solved independently. The resulting optimization outputs are statistically evaluated using probability density functions and quantile ranges to quantify airport-specific uncertainty ranges for LH_2 supply costs and infrastructure sizing.

3. Results / Conclusions

The results show that LH_2 supply costs differ substantially between airport case studies, not only in terms of median cost levels but also in terms of uncertainty ranges. Overall, LH_2 supply costs decrease significantly between 2035 and 2055, for example from approximately 12–14 USD/kgH_2 in 2035 to around 3–4 USD/kgH_2 in 2055 for Lisbon as illustrated in Fig 2. Parameter uncertainty accounts for significant variability in LH_2 supply costs. For each milestone year and airport case, the uncertainty range for airport LH_2 supply costs is between 1–3 USD/kgH_2. The results further highlight that LH_2 airport infrastructure planning should not rely on a single deterministic cost estimate or one generic airport configuration. Overall, the study demonstrates that Monte Carlo-based optimization can support more robust planning of LH_2 supply infrastructure for H_2-powered aviation by translating techno-economic uncertainty into actionable infrastructure insights.

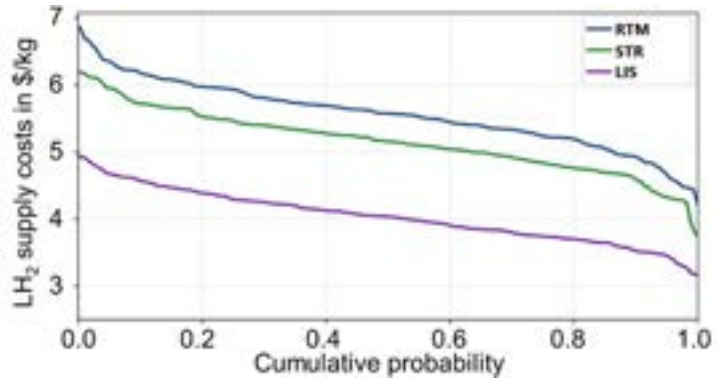


Figure 2. *Comparison of LH_2 cost ranges for the airports of the case study in 2055*

Uncertainty-Aware Cryogenic Hydrogen Tank Design Optimization for Regional Turboprop Aircraft

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1. Introduction / Objectives

Liquid hydrogen is a promising energy carrier for reducing the climate impact of regional aviation, but its practical use requires cryogenic liquid hydrogen (LH2) storage systems that are both lightweight and safe. For regional turboprop aircraft, the aircraft-integrated LH2 tank is a kay safety and performance driver, since heat leak, self-pressurization and boil-off gas generation can lead to venting during airport operation. Therefore, maintaining the tank pressure below maximum allowable value for a prescribed dormancy time, such as turnaround or overnight parking, is essential.

The objective of this work is to develop an uncertainty-aware early-stage LH2 tank design framework for an ATR72-class hydrogen-powered regional aircraft. The framework links tank gravimetric efficiency with a probabilistic dormancy-time safety constraint, replacing ad-hoc deterministic safety factors with a robust design loop. The proposed approach aims to identify tank designs that satisfy operational safety requirement under manufacturing, material-property and operating-condition uncertainties.

2. Methodology

The proposed framework couples a fast zero-dimensional sizing model with a one-dimensional transient thermal model to support early-stage LH2 tank design for an ATR72-class regional turboprop aircraft. The considered tank is a cylindrical vessel with hemispherical end caps, integrated within the aft-fuselage installation envelope. A three-layer architecture is assumed, consisting of an inner Type-V composite layer, a foam insulation layer and an outer Type-V composite protective layer.

The zero-dimensional model uses top-level aircraft requirements as boundary conditions,

mainly the required LH2 block fuel and the maximum allowable outer tank diameter imposed by the fuselage envelope. These fixed inputs are combined with design variables including maximum operating pressure, filling pressure, insulation thickness, protective-layer thickness and vapor volume fraction. The mass of each layer is estimated from the corresponding volume and material density, allowing the tank dry mass and gravimetric efficiency to be evaluated.

The resulting tank geometry is introduced to a one-dimensional transient model able to capture filling, dormancy, fuel withdrawal and mission operation. In the present work, this model is mainly used to predict liquid and vapor temperature evolution, self-pressurization, venting onset and dormancy time. A sensitivity analysis is first performed to identify the dominant design parameters. The results show that insulation thickness and maximum operating pressure have the strongest influence on dormancy time and gravimetric efficiency, while filling pressure has a negligible effect in the investigated design space.

A multi-objective optimization is then implemented on the 0D-1D framework, aiming to maximize both dormancy time and gravimetric efficiency. The resulting Pareto front provides a set of optimal design candidates from which an end-user can select the most suitable safety-performance compromise.

Finally, aleatoric uncertainties related to manufacturing tolerances, operating conditions and material / thermophysical properties are propagated using Latin Hypercube Sampling. Candidate Pareto design are evaluated through a safety-aware loop until the probabilistic dormancy constraint: $P(\tau_{dorm} > \tau_{dorm,min}) \geq 99.7\ \%$ is satisfied.

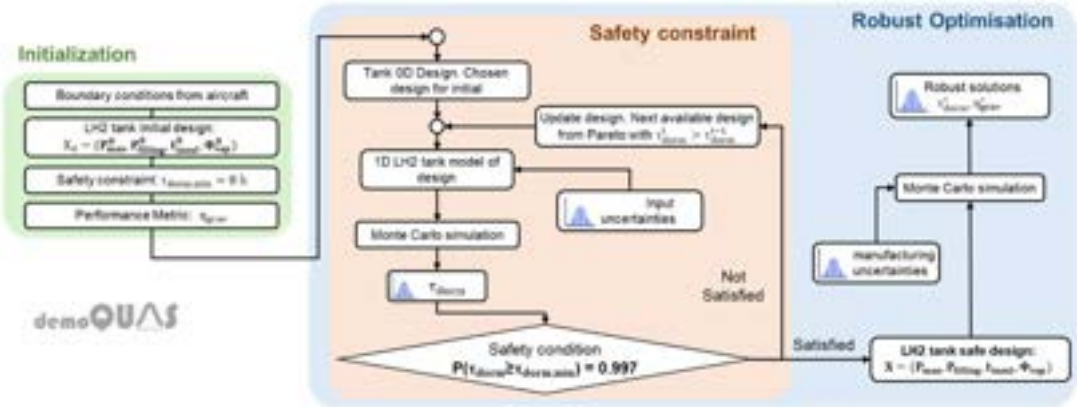


Figure 1. *Uncertainty-aware tank sizing framework.*

3. Results / Conclusions

The deterministic optimization produced a clear Pareto trade-off between dormancy time and gravimetric efficiency. Design with increased insulation thickness and higher operating pressure achieved longer dormancy times, but with a penalty in gravimetric efficiency.

Uncertainty propagation showed that a nominal design targeting an 8 h dormancy time was not sufficiently robust, since part of the dormancy time distribution fell below the required safety threshold. The proposed safety-aware loop therefore moved along the Pareto front until the probabilistic dormancy constraint was satisfied. For the investigated cased study, four design-loop iterations were required. The final robust design indicated that an additional margin of approximately 1 h on the nominal design is needed to ensure that uncertain dormancy time distribution remains above the 8 h requirement. This demonstrates the need for uncertainty-aware LH2 tank sizing instead of purely deterministic safety.

A Validated Computational Framework for Cryogenic Tank Filling

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1. Introduction / Objectives

The aviation sector's pursuit of net-zero emissions by 2050 has placed liquid hydrogen at the forefront of next-generation propulsion concepts. However, the practical adoption of liquid hydrogen in commercial aviation hinges on the development of efficient, lightweight and safe cryogenic storage systems. A critical aspect of such systems is the filling process of the tank, during which intense thermodynamic phenomena such as flash boiling, rapid cool-down transients and two-phase flow dynamics govern the tank's thermal and structural behavior.

In this work, a Conjugate Heat Transfer Computational Fluid Dynamics modelling framework is developed and validated against experimental data to investigate the filling regime of cryogenic tanks. In particular, the transition from liquid nitrogen to liquid hydrogen as working media within a unified modelling framework is assessed, alongside an evaluation of its scalability to different inlet configurations and filling techniques.

2. Methodology

The modelling framework, implemented in ANSYS Fluent, is built upon a two-dimensional axisymmetric CFD approach, employing the Volume of Fluid (VOF) method for the two-phase flow representation, the Lee model for the simulation of evaporation and condensation phenomena and the Continuum Surface Force (CSF) model for surface tension effects. Conjugate Heat Transfer (CHT) is integrated to capture the thermal interaction between the fluid and the tank wall. Regarding the modelling of turbulence, a dedicated study was performed comparing the k-ω SST and k-ε models, with the k-ε model retained as it achieved lower computational cost without compromising the predictive accuracy.

A key modelling consideration is the treatment of the tank inlet boundary condition, where a time-dependent void fraction is introduced to replicate the two-phase mixture inlet observed in the liquid hydrogen (LH_2) filling experiments. For each test case, the influence of the Lee model coefficients was assessed through sensitivity analyses. The coefficients tuning was shown to be dictated primarily by the underlying physics of each case.

The framework is validated against two experimental datasets: the liquid nitrogen (LN_2) open-vent filling experiments of Kang et al. and the LH_2 no-vent fillings tests of Moran et al., with model performance benchmarked through pressure and temperature history comparisons at multiple monitoring points on both fluid and solid regions. Building on the validation, the framework's scalability is evaluated by applying it to an alternative liquid inlet configuration, without any retuning of the model coefficients.

3. Results / Conclusions

A CHT-CFD modelling framework for cryogenic tank filling was successfully developed and validated against experimental data. As depicted in Figure 1, the framework accurately reproduces the experimentally observed thermal and two-phase flow fields throughout the filling process. Further, both qualitative and quantitative agreement is attained for all monitored quantities between the simulations and experiments for each test case examined.

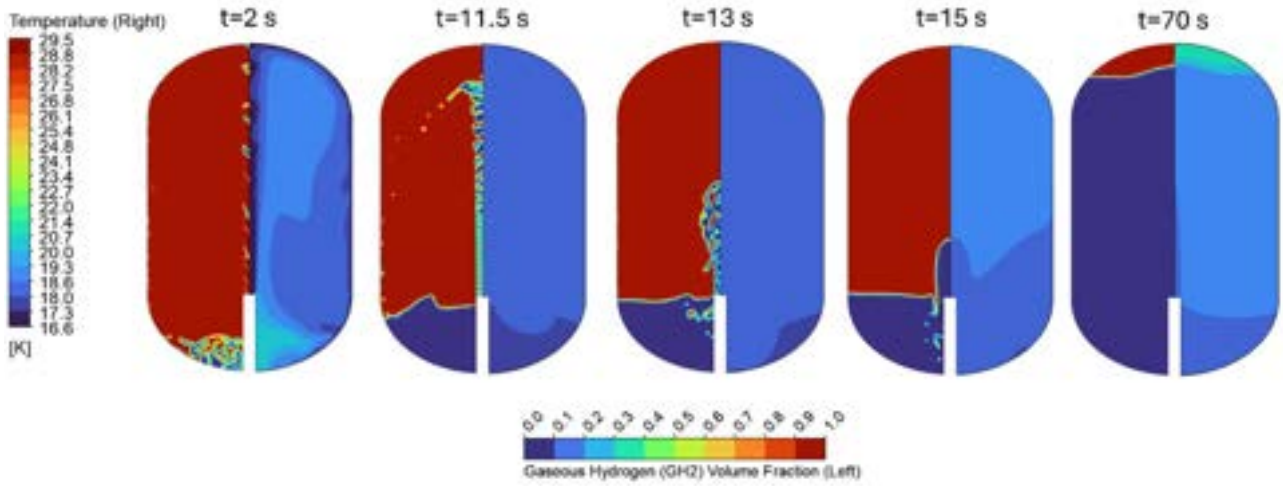


Figure 1. *Phase (left) and temperature (right) contours during the filling (LH_2 – Bottom diffuser case)*

The transition between working media within a unified framework is proven to be feasible, although comparable experimental data for both LH_2 and LN_2 would be necessary to quantify the associated modelling uncertainty. A notable limitation that was identified, is the inability of the standard employed multiphase models to inherently reproduce the flash boiling phenomena, which appear to require dedicated treatment. Additionally, variations in inlet configuration are shown to not compromise the predictive accuracy of the framework, confirming the direct applicability.
Since the transition between working media is shown to be achievable, the present approach, after careful tuning of the phase change models, could exploit the greater accessibility of LN_2 experimental data to investigate LH_2 cryogenic storage systems for commercial aviation applications. Moreover, the findings suggest that a versatile modelling framework, applicable across different working media, filling techniques and inlet configurations holds significant potential as a tool for parametric studies and design optimization of cryogenic tanks for hydrogen powered aircraft.

An Experimental Two-Dimensional Tank Study of Sloshing Dynamics

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1. Introduction

The HASTA (Hydrogen Aircraft Sloshing Tank Advancement) project investigates sloshing phenomena in hydrogen aircraft tanks, addressing a key challenge in the adoption of hydrogen as a fuel for future aviation systems. The motion of liquid hydrogen during flight may significantly affect vehicle stability, safety, structural integrity and performance. The project therefore examines fluid behaviour under representative operating conditions and develops predictive methodologies to support tank design and optimisation.
HASTA combines experimental activities with advanced numerical approaches to analyse sloshing dynamics. In particular, it aims to develop tools capable of describing hydrogen behaviour under non-isothermal sloshing conditions, where thermal and fluid-dynamic phenomena are strongly coupled.

The experimental campaign covers configurations of increasing complexity. It begins with benchmark cases, including isothermal vertical sloshing experiments in a two-dimensional water-filled cell for model validation, and progresses to three-dimensional geometries, non-isothermal conditions and replacement fluids. The final stage involves cryogenic experiments with hydrogen under realistic operating conditions.
The present work applies mathematical tools for liquid-behaviour characterisation to the simplest test case: the isothermal two-dimensional cell. Despite its elementary configuration, the setup exhibits complex nonlinear dynamics, highlighting the need for robust mathematical and numerical tools to predict sloshing behaviour in future hydrogen-powered aircraft.

2. Methodology

The quasi-two-dimensional cell was subjected to periodic vertical acceleration to excite the first symmetric and asymmetric sloshing modes at different filling ratios. This controlled forcing enabled the liquid modal response to be investigated under resonance conditions. The free-surface dynamics were recorded using a high-speed camera with high temporal and spatial resolution.
The video data were processed using wavelet analysis, proper orthogonal decomposition (POD) and cross-wavelet analysis. This data-driven framework extracted physically relevant features to support the development of reduced-order and predictive models of sloshing dynamics.
Wavelet analysis identified the time-resolved sloshing frequencies and their evolution under different forcing conditions, capturing transient and non-stationary behaviours not fully described by Fourier-based methods. POD decomposed the flow field into energetic coherent structures, identifying the dominant spatial modes associated with symmetric and asymmetric sloshing.
Cross-wavelet analysis examined phase relationships and coupling mechanisms between modal contributions, revealing intermittent coupling and modulation effects dependent on filling ratio and excitation amplitude. Nonlinear corrections to the modal dynamics were also observed, indicating departures from ideal linear behaviour under relatively simple forcing conditions.
The combined POD and wavelet framework showed that energy is redistributed across multiple spatial and temporal scales, rather than confined to a single dominant mode. This result is relevant to reduced-order modelling, since predictive tools must account for nonlinear modal interactions and inter-modal energy transfer.
Overall, the proposed methodology provides a framework for characterising sloshing dynamics in confined geometries. Results from the quasi-two-dimensional configuration represent a step towards robust numerical models for realistic hydrogen tank systems.
Representative snapshots extracted from the recorded videos are shown in Fig. 1.

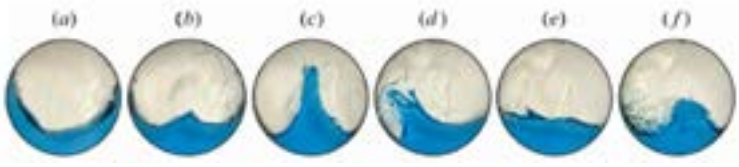


Figure 1. *Snapshots of the flow field for the symmetric response. (a–c) Regular oscillatory regime at t = 5.06 s, 5.12 s and 5.19 s; (d–f) intermittent breakdown event at t = 12.52 s, 12.55 s and 12.61 s*

3. Results

By applying a data-analysis technique combining wavelet analysis and proper orthogonal decomposition (POD) to the recorded fluid-phase dynamics, it was possible to extract a statistical representation of the sloshing-mode topology, as shown in Fig. 2(c), and to characterise the temporal dynamics of each individual mode in both the time and frequency domains, as illustrated in Figs. 2(a,b).

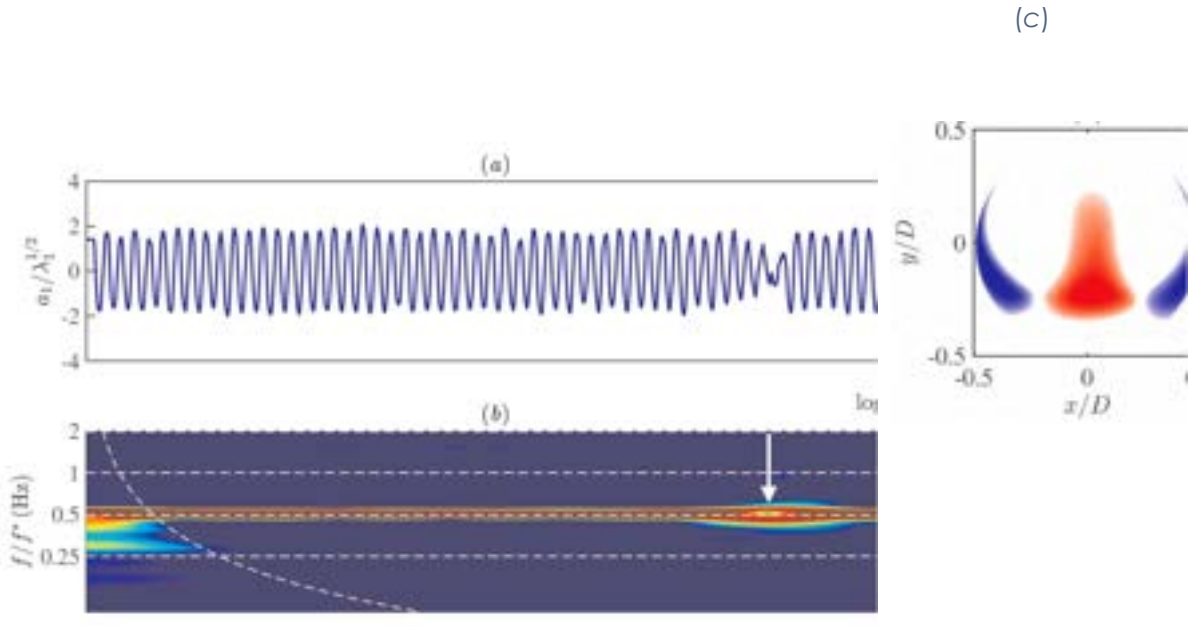


Figure 2. *First POD mode extracted from the symmetric sloshing regime: (a) first POD temporal coefficient; (b) continuous wavelet transform of the corresponding temporal coefficient; (c) spatial structure of the first POD mode.*

The experimental results were subsequently used to formulate a reduced-order model suitable for geometry design and for investigating the system dynamics through a low-fidelity modelling tool.

Energy and Fuels: Radical approaches towards 100% renewable energy and climate neutrality

Chaired by:
Dr. Andreas Sizmann (Bauhaus Luftfahrt, Germany

Jet fuel production via hydrothermal liquefaction of agricultural residues: Economic and environmental performance

Leonard Moser, Christina Penke, Valentin Batteiger
Bauhaus Luftfahrt, Germany

1. Introduction

The European Union funded project CIRCULAIR develops key technologies for the conversion of abundant agricultural residues into jet fuel via hydrothermal liquefaction (HTL). HTL can convert various organic feedstock into biocrudes, the resulting biocrudes can be further treated and upgraded into liquid hydrocarbon fuels. In CIRUCLAIR, aqueous feed slurries with about 10-15% dry matter content were processed at temperatures of 300-350°C and sufficiently high pressure to keep water in a liquid state. HTL is in particular attractive for wet residue and waste streams as feedstock drying is not necessary. Manure and straw represent the most abundant agricultural residues within Europe and were therefore in the focus of CIRCULAIR. The project takes a holistic approach that aims at valorizing all major process streams that result from HTL, in particular process heat is generated from the organic content in the process water and evolving CO_2 streams are purified for additional fuel synthesis.

2. Methodology

The experimental implementation of the CIRCULAIR project was realized by several project partners and involved various pilot scale demonstrations. In particular, at the premises of the project partners pilot plants were operated for HTL, wet oxidation of the HTL process water and biocrude upgrading. Several analytical techniques were applied to analyze intermediate and final products. Full detail on the methodologies of that were used for various aspects of experimental project implementation is beyond the scope of this abstract. The system analyses are based on a process model that represents the full fuel pathway. Kinetics models were developed to provide an improved understanding of trade-off and the coupling o process steps. The techno-economic modelling is based on a levelized-cost of fuel approach. For the life-cycle analyses, global warming potential (GWP) is chosen as a key parameter of environmental impact. The live-cycle analyses were conducted with the software Brightway2.

3. Results

The experimental implementation involved pilot-scale HTL campaigns with various mixtures of manure and straw. The resulting biocrudes were upgraded to liquid hydrocarbon with a yield of more than 40% in the jet fuel range. The resulting kerosene sample fulfilled jet fuel specifications including a nitrogen content < 2 ppm, which was a major target of the project. Unlike synthetic paraffinic kerosenes (SPK), such as HEFA-SPK or Fischer-Tropsch SPK, the HTL jet fuel contained significant share of cyclo-alkanes and a moderate aromatic content. In consequence, the density of the fuel is more similar to conventional jet fuel and may therefore qualify as stand-alone drop-in fuel or as favorable blendstock for future fully synthetic drop-in fuel blends. The project demonstrated process water clean-up and process heat generation by wet oxidation, significantly reducing, if not eliminating the external heat demand of HTL. Furthermore, evolving gas streams were characterized and CO_2 purification schemes for additional methanol synthesis from CO_2 and green hydrogen were developed.

Likewise, treatment methods for HTL solids, which are also generated as a by-product, were developed and the application of solids for agricultural soil amendment and carbon sequestration was demonstrated.
The techno-economic analysis shows that fuel production cost can be cost-competitive with current renewable jet fuel production pathways. The live-cycle analysis suggests compliance with the emission reduction threshold as it is set out in the EU-Renewable Energy Directive, while the sequestration of HTL solids as well as potential credits for emission avoidance in agriculture due to changed manure handling practices represent negative contributions to the GHG balance.

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Sustainable Aviation Fuel from Sunlight and Air: Progress and Perspectives

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[2] Synhelion AG, Switzerland
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1. Introduction / Objectives

Beyond well-discussed climate targets, SAF promises strategic advantages for aviation by independence from fossil oil and by enabling more diversified supply chains, which is increasingly relevant in a geopolitically volatile world. Early order-of-magnitude resource assessments suggest that less than 1% of global desert area would suffice to harvest the solar energy required for projected global SAF demand. The EU project SUN-to-LIQUID II advances a solar-thermochemical route to produce SAF directly from sunlight, water, and CO_2. The process couples a high-flux concentrating solar field with a two-step ceria-based redox thermochemical process for syngas production, and Fischer-Tropsch (FT) synthesis, demonstrated at a solar research plant at IMDEA Energía in Móstoles, Spain. The project aims to advance the solar fuel technology to higher efficiency and yield at TRL 4–5, and at system level to assess the production potential, production cost, and environmental impact for future commercial solar fuel deployment.

2. Methodology

The analytical core of this work is an integrated process model of a future commercial multi-MW solar fuel plant. The model couples a high-flux heliostat field and solar tower with a two-step redox reactor, high-temperature thermal storage, sensible heat recuperation, and a FT synthesis and refining unit. Mass and energy balances are resolved for full-year operation. The study includes a comparison of different receiver concepts, building on performance models for absorbing gas receivers and multi-aperture receiver-reactor configurations ,

which face several challenges when scaled to multi-MW plants. The more favorable volume-to-surface ratio at larger scales reduces relative thermal losses, which is particularly advantageous for high-temperature processes. However, increased solar field sizes lead to decreased optical efficiencies, which negatively impacts the CAPEX requirements and the resulting production cost. Nevertheless, achieving high heat recuperation efficiency at scale remains a primary engineering challenge, alongside the integration of low- and high-temperature direct air capture (DAC) variants, exploiting solar waste heat in arid locations. Additional systemic constraints analyzed include ceria supply and regeneration for 3D-printed reactor structures, infrastructure availability at desert sites, and workforce and financing risks.

The environmental performance will further be assessed through a full well-to-wake prospective life-cycle analysis – encompassing fuel combustion –, using forward-looking inventory data to reflect a future commercial plant rather than today's supply chains. This enables a quantitative comparison with alternative SAF options and the fossil kerosene reference case under projected carbon price scenarios. The techno-economic analysis quantifies CAPEX, OPEX, learning curve effects, and weighted average cost of capital (WACC) across representative desert locations, identifying key cost drivers and their sensitivity.

3. Results / Conclusions

Preliminary modeling indicates that a fully integrated solar fuel plant – incorporating DAC, heat recuperation, and tail gas recycling – can achieve well-to-wake CO_2 savings exceeding 80% relative to fossil kerosene. The scale-up study identifies key systemic constraints and technology gaps – including high-temperature heat management, DAC integration, and infrastructure requirements at desert sites – that must be addressed on the pathway to multi-MW deployment. The ongoing TEA and prospective LCA will quantify environmental and economic performance under current and projected carbon price scenarios. This leads to higher direct operating costs as carbon pricing mechanisms, comprising emissions trading systems and carbon taxes, are needed to accelerate the economic case for the more expensive low-carbon alternatives. The results provide valuable input for scenario assessments for future climate-friendly aviation, which then integrate both strategic investments in aircraft efficiency and transition to SAF and evaluate the most cost-effective path towards climate-friendly aviation.

Investigation report on SAF application strategies of major European aircraft manufacturers

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1. Introduction / Objectives

The decarbonization of aviation represents a major technological and regulatory challenge for the aerospace sector. In the short to medium term, Sustainable Aviation Fuels (SAF) constitute the most viable pathway to reduce lifecycle CO_2 emissions while maintaining compatibility with existing aircraft and fuel infrastructure. European policy instruments such as

ReFuelEU Aviation and international qualification standards are accelerating SAF deployment, creating new airworthiness and certification challenges for aircraft and engine manufacturers.
This work investigates the SAF application strategies adopted by major European OEMs—Airbus, Rolls-Royce and Safran—and evaluates their technology deployment, verification approaches and certification readiness. The study aims to assess how industrial initiatives and European research projects (e.g., JETSCREEN , PACIFIC , SMR ACAP) contribute to fuel-system verification, combustion validation and regulatory adaptation towards full SAF compatibility.

2. Methodology

The study is based on a systematic review of publicly available technical documentation, OEM demonstration reports, international certification standards and European collaborative research programs under Clean Aviation, Clean Sky, Horizon 2020 and Horizon Europe. Emphasis is placed on projects such as JETSCREEN, PACIFIC and SMR ACAP, which provide experimental data on fuel chemistry, combustion behavior, emissions formation and system compatibility relevant to certification.
The analysis framework first identifies the SAF production pathways prioritised by each OEM, including HEFA, Alcohol-to-Jet (AtJ), Power-to-Liquid (PtL) and hydrogen-derived e-SAF. It then reviews engine test-bed campaigns and aircraft flight demonstrations performed at high blending ratios and 100% SAF, examining the scope and depth of verification activities. Special attention is given to operability margins across the flight envelope, emissions performance and deposit formation tendencies.
In parallel, the methodology evaluates fuel-system verification practices, including assessment of pumps, valves, injectors, seals, elastomers and metallic components exposed to low-aromatic fuels, as well as lubricity management and long-term durability considerations. Certification workflows are analysed in relation to ASTM D4054 qualification procedures and ASTM D7566 fuel specifications, together with their interaction with EASA and international regulatory guidance.
Finally, the study examines market-enabling mechanisms such as the Book and Claim approach implemented by Airbus , as well as strategic partnerships with SAF-related organisations and additional industrial initiatives aimed at accelerating SAF deployment. These actions are analysed in terms of their contribution to market scalability, regulatory alignment and the integration of sustainability objectives with airworthiness and certification frameworks.
Comparative tables are developed to map SAF pathways, test evidence, verification strategies and certification roadmaps across Airbus, Rolls-Royce and Safran, enabling a structured cross-OEM assessment of technical and regulatory readiness.

3. Results / Conclusions

The findings indicate that 100% SAF operation is technically feasible for current and next-generation aircraft and engines, provided that structured verification and qualification processes are followed. European research initiatives play a critical enabling role by linking fuel chemistry, combustion behavior and system compatibility to certification readiness.
While OEM strategies differ according to their industrial roles—engine-centric validation for

Rolls-Royce, hydrogen-oriented e-SAF focus for Safran, and aircraft-level integration and market facilitation for Airbus—all converge toward full SAF compatibility by 2030. Overall, the report concludes that SAF deployment in Europe is not solely a technical challenge but a systemic transformation involving fuel producers, manufacturers, regulators and operators. European industrial strategy and coordinated policy instruments are central to ensuring safe, scalable and internationally harmonized SAF adoption by 2030 and beyond.

Integration of a multi-stack fuel cell system controller based on an aviation-relevant real-time operation system

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DLR – German Aerospace Center

1. Introduction / Objectives

The use of hydrogen-electric main propulsion systems based on polymer electrolyte membrane fuel cells is one of the options being discussed for achieving the aviation sector's emissions reduction targets.
In this regard, the adaption of aviation-relevant control electronics to operate high power multi-stack fuel cell systems and enable an appropriate automated and fail-safe power management of the energy system is a challenge, as a large amount of data has to be processed . In this work, an aviation-relevant supervisory controller is integrated into a megawatt multi-stack fuel cell system and data-logging on the controller is validated in a first test campaign.

2. Methodology

The fuel cell system architecture applied in this work is based on a modular approach with two fuel cell modules connected in series, while up to six of such serial pairs are coupled in a parallel configuration. The fuel cell modules with 100 kW net power are off-the-shelf commodities equipped with auxiliary components and an integrated module controller.

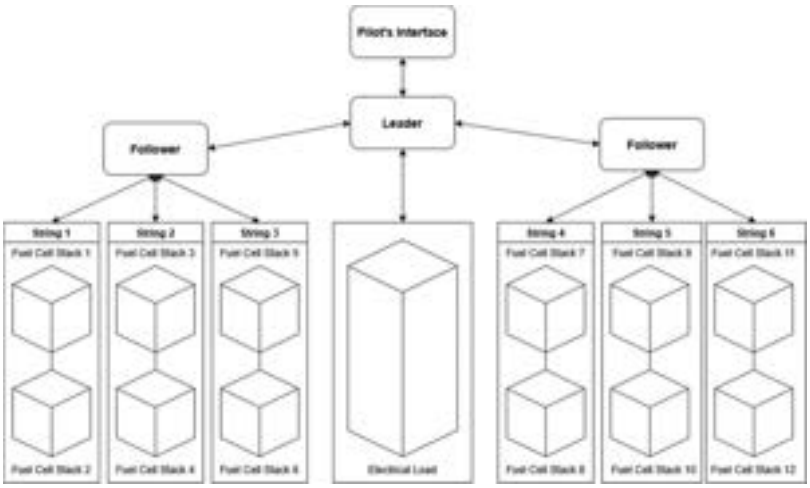


Figure 1. *Implemented system Controller.*

The developed system controller based on a certified real-time operation system is designed as a supervisory controller comprising two levels. An overview of the system architecture is shown in Figure 1. On the first level, the leader controller handles the integration of the communication interfaces between the pilot's user interface, the electrical load and the follower controller. On the second level, the follower controller manages the fuel cell system communication. The data logging of the developed controller is tested in normal and faulty fuel cell operation. In the first part of the test campaign, the controller's dynamic performance is assessed while stationary and transient load profiles are applied to the fuel cell system. The second part of the test campaign targeted system failures are induced to the system. These errors can lead to a shutdown which is induced by the module itself. Hence, with these tests the appropriate error detection and monitoring by the controller is checked and validated. The recorded system parameters are compared with values measured by the facility control system. The temporal behavior of the supervisory controller is examined and misalignments in the data recording are checked for failure-critical impacts.

3. Results / Conclusions

The design concept has been successfully tested and implemented. The controller's dynamic requirements were fulfilled. The measured variables are received on the user interface with a slight time delay, which can be attributed to the CAN controller, whereby all measured variables are recorded at the correct time. The time difference between the measurement data recordings is constant. Based on the findings, an approach to error detection and handling is validated that enables the controller to forward the error message to the user interface faster than the normal operating data. Further studies should focus on to supplementing the controller with control and regulation tasks for automated fuel cell and powertrain system operation. In addition, the system architecture should be expanded to include parallel DCDC converters and more complex power management strategies should be implemented on the aviation-relevant controller.

Acknowledgement: The project is supported by the Clean Aviation Joint Undertaking and its members in the framework of Grant Agreement n° 101102020 – AMBER. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

Weight Reduction in Aviation Battery Systems Through Uncertainty-Aware Modeling Within Specified Safety Levels

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1.Introduction / Objectives

The pathway towards radical 100% renewable energy and climate neutrality via e-aviation, as well as concepts such as the ultra-efficient regional aircraft (UREA) rely on suitable battery system designs, optimized for gravimetric and volumetric energy density under most stringent safety requirements imposed by the aviation use case. Thermal runaway propagation (TRP) remains a critical challenge, as mitigation measures like thermal barriers and cooling increase system mass and volume, reducing aircraft range and payload.
High-fidelity simulation approaches, such as finite element method (FEM) or computational fluid dynamics (CFD) models, are widely used in the design process. However, this process requires increased effort because TRP model predictions are universally affected by parameter uncertainties stemming from cell-to-cell variability, poor test repeatability, and unmeasurable thermal and kinetics parameters . Evaluating these uncertainties requires largescale parametric studies, which are computationally impractical using heavy FEM/CFD tools during early design stages.

2.Methodology

This work presents an uncertainty-aware framework that infers parameter distributions from experimental data and propagates them through a reduced-order thermal model, enabling probability-based sizing of thermal barriers and cooling systems for safer, lighter aviation battery packs. The methodology (Fig. 1) comprises reduced-order model development, uncertainty calibration, and uncertainty-aware design analysis.
A computationally efficient thermal runaway propagation (TRP) model is first developed for large-scale parametric studies. It combines an empirical thermal runaway heat source with a lumped thermal network (LTN) module representation. The heat source is derived from Accelerating Rate Calorimetry (ARC) measurements following the approach of Hoelle et al. , yielding a temperature-dependent heat generation profile ($Q(T)$). In the Lumped Thermal Network, each cell is a single thermal node, while heat propagation is captured in all three spatial directions.
To account for prediction uncertainties, the model is calibrated using experimental propagation data. First, a global sensitivity analysis (GSA) identifies the most influential parameters, reducing the calibration space to dominant uncertainty sources. These influential parameters are subsequently calibrated via Approximate Bayesian Computation (ABC). Prior parameter distributions, defined from experimental and literature data, are updated using TRP measurements to obtain posterior distributions capturing cell-specific uncertainty. Finally, uncertainty is propagated via Monte Carlo simulations while sweeping thermal barrier resistance and heat dissipation capabilities. The resulting design space is

evaluated by propagation prevention probability, identifying the minimum thermal protection and cooling requirements needed to satisfy a specified safety confidence level.

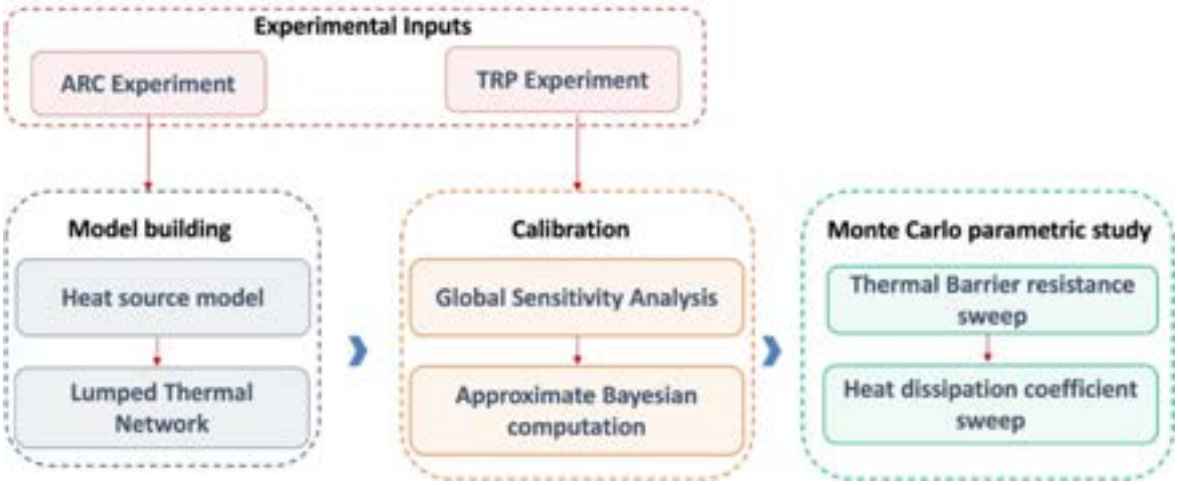


Figure 1. *Methodology roadmap.*

3. Results / Conclusions

A reduced-order thermal runaway propagation model has been successfully developed and integrated with an ARC-derived heat source model, providing a computationally efficient basis for large-scale uncertainty and design studies. Initial analyses have established the parameter space for uncertainty quantification and identified the experimental data required for calibration.

The ongoing calibration and uncertainty analysis will generate probability-based design maps linking thermal barrier resistance and cooling capability to propagation prevention performance. These results will enable the identification of minimum thermal protection requirements required to achieve specified safety confidence levels.

By explicitly accounting for uncertainty in thermal runaway behavior, the proposed framework supports more informed design decisions than conventional deterministic approaches. The methodology is expected to contribute to the development of aviation battery systems that satisfy stringent safety requirements while minimizing mass and volume penalties.

Acknowledgement: This work is conducted within the framework of the EU-funded Clean Aviation project MODABAT (GA: 101251224).

Additive Manufacturing

Chaired by:
Prof. Teresa Morgado (Polytechnic University of Lisbon, Portugal)

The Impact of Additive Manufacturing in the Aerospace Industry: Challenges and Opportunities

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ISEL- Instituto Superior de Engenharia de Lisboa, Portugal

1. Introduction / Objectives

The aerospace industry faces increasing demands to develop components that are simultaneously lighter, more complex, and more durable. Traditional manufacturing methods struggle to meet these requirements while maintaining cost-effectiveness and production speed. Additive manufacturing (AM) represents a promising solution, offering unprecedented design flexibility and enabling the creation of complex geometries previously unattainable through conventional methods . AM technologies have been used for aerospace applications, including Selective Laser Melting (SLM) mechanical components, Laser Melting Deposition (LMD) for flexible manufacturing and remanufacturing, Electron Beam Selective Melting (EBSM) for large titanium components, and Wire Arc Additive Manufacturing (WAAM) for structures. However, many challenges are presented, namely industrial implementation. This work explores the current state of AM in aerospace, analyzing both its transformation potential and the substantial barriers that prevent widespread adaptation of this technology.

2. Methodology

This work synthesizes findings from contemporary research on additive manufacturing applications in the aerospace industry through systematic literature analysis. The research methodology encompasses in literature selection of Peer-reviewed papers, technical reviews, and industry reports published between 2000-2026 were examined, focusing on AM technologies applied to aerospace components manufacturing, quality assurance methodologies, and regulatory frameworks. The material and microstructural issues as porosity , residual stress and anisotropy were studied. The quality assurance and defect detection were discussed. Regulatory and certification barriers, scalability, post-processing requirements, and process reproducibility and standardization were identified as challenges. Opportunities assessment is also one of the objectives of this research. Recommendations for Industrial adoption are suggested.

3. Results / Conclusions

This research reveals that AM technologies demonstrate significant promise for aerospace manufacturing, nevertheless its potential remains constrained to few mechanical parts. The global additive manufacturing market, valued at approximately $21.9 billion in 2025 , is projected to reach $647.7 billion by 2035 at a compound annual growth rate of 22-23%, with aerospace remaining one of the dominant sectors. This rapid market expansion reflects

growing recognition of AM's potential to address critical aerospace challenges, including fuel efficiency, operational costs, and rapid prototyping cycles. Market projections for Figure 1 are based on industry forecasts and research publications.

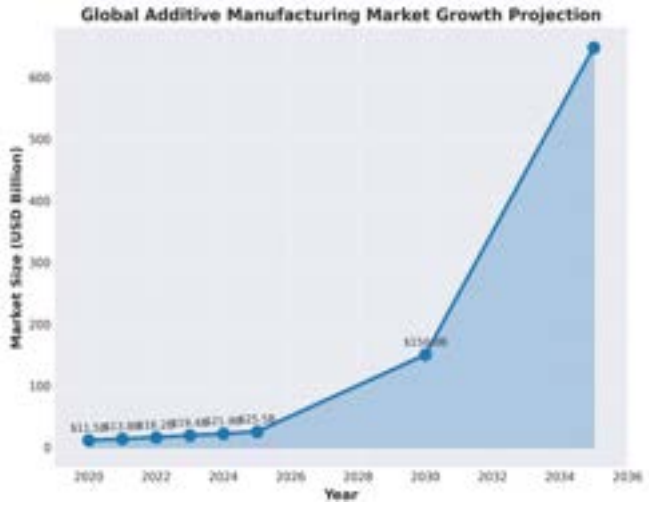


Figure 1. *Global Additive Manufacturing Market Growth Projection.*

It is concluded that there are critical challenges as mechanical unreliability, defects control fragility, and quality assurance gaps that continue to compromise operational reliability of additive manufacturing components and structures in aerospace systems. It is also concluded that regulatory and certification barriers remain substantial obstacles. Nevertheless, emerging opportunities are evident through enhanced process optimization, advanced in-situ monitoring, and predictive modeling approaches. Success requires cooperation among manufacturers, academies, regulators, and certification to establish standardized qualifications. With continued development in materials formulation, process control, and digital integration, AM will progressively grow in aerospace industry. This transformation will require sustained investment in quality assurance and regulatory frameworks.

Residual stresses evaluation in cold spray process using digital image correlation

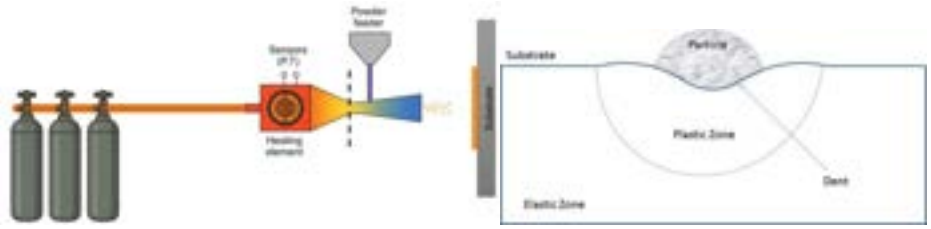
Abouhamzeh M, Stamoulis K.
Amsterdam University of Applied Sciences, Netherlands

1. Introduction / Objectives

During the cold spray process, continuous impact of high-velocity particles on the substrate (a) generates high local strain in the coating and in the vicinity of the interface and contributes to the development of residual stress in both the deposited coating and the substrate (b).

This is an attribute that makes cold spray an attractive option for restoration and repair processes by reducing the surface residual stresses in the deposit region. To fully exploit these

benefits, the residual stress state is needed to be accurately measured and correlated with the process parameters. The objective of this research is to measure near-surface residual stress fields in cold sprayed aluminum samples with novel, affordable and high-resolution techniques which remain insufficiently explored in the literature.



(a) (b)

Figure 25. *(a): Cold spray deposition process, (b): Evolution of stresses induced by CS at and underneath the surface .*

2. Methodology

Near-surface residual stresses in cold-sprayed metallic coatings can be measured using various methods that have been earlier discussed in the literature.
Continuing our group research on evaluation and testing of cold sprayed parts, the current research approach combines Digital Image Correlation (DIC) with Incremental Hole-Drilling (IHD). Micro-hole drilling increments will be performed while DIC analysis will be used to determine the displacement fields through curvature measurements. The resulting displacement mapping will be converted into surface strain fields which will then be used to calculate the original residual stress distribution through inverse analysis and finite element (FE) modelling . The main steps of the proposed procedure are:

- Images are acquired before and after each incremental hole drilling. Through correlation of the image pairs, displacement maps are determined.
- Subtract rigid body motion from the displacement field and calculate surface strain fields. This step includes significant and time-consuming image correlation.
- Extract radial/azimuthal displacement/strain fields around hole in accordance with the standard for hole- drilling testing ASTM-E837.
- Develop FE models to simulate the stress relaxation process during drilling and calculate the original residual stress from the measured released strains. In case if the hole drilling proves impractical, a layer removal approach will be employed as an alternative. The layer removal method is a test method based on the concept that removing a layer from the surface of a plate having residual stress changes the force and moment equilibrium acting in the remaining piece. This method is used to determine the through-thickness residual stress distribution in the material. A critical task in the current study is to remove ultra-thin layers (around 10 microns) every step and measure the updated curvature of the samples (they can be 10 by 10 cm) by DIC.

3. Results / Conclusions

The main outcome from this study will be the determination of near surface residual stresses distribution in cold sprayed Aluminum substrates. A key challenge is the experimental

feasibility of performing highly controlled micro drill increments. The planned increments for hole drilling are 10 µm steps for coatings thinner than100 µm or 20–50 µm steps for thicker coatings. There is also speed requirement in the drilling process to avoid change of stress distribution induced by the drilling itself.
The induced residual stresses significantly affect the structural integrity of aircraft components and eventually the remining lifetime of the structure. The intended accurate characterization of the stress field near the surface in the cold sprayed part can be tailored in follow-up research to increase the damage tolerance of the repaired component and therefore can support the structural integrity of the structure.

Effect of Printing Parameters on the Electrical Resistance of FFF-Printed Piezoresistive Sensors Based on PEI/CNT/CB Composite Filament

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1. Introduction / Objectives

Fused Filament Fabrication (FFF) enables the direct, in-situ fabrication of piezoresistive strain sensors onto aerospace structures, offering a scalable and geometry-flexible manufacturing route that eliminates parasitic weight and complex adhesive bonding protocols in structural health monitoring (SHM) applications. In these smart configurations, the baseline electrical resistance (R_0) critically governs the nominal operating window and ultimate gauge factor sensitivity of the printed sensor element; yet its systematic dependence on FFF deposition process parameters remains poorly characterized in existing literature. This study systematically investigates how critical primary print parameters, specifically deposition speed and layer thickness, influence R_0 in line sensors printed from a custom high-performance polyetherimide (PEI) filament modified with a hybrid carbonaceous network (3 wt% CNT and 1 wt% CB) . Furthermore, freely extruded fibers are incorporated as a comparative baseline to isolate the exact role of nozzle–substrate interaction in shaping the carbon-based internal percolation network.

2. Methodology

Prior to the core experimental phase, the sensitivity of R_0 to mechanical variations in the extruder drivetrain was assessed. Free sensor fibers were extruded through a 0.8 mm nozzle at 1, 3, 5, and 10 mm/s under four assembly torque levels (1, 3, 5, and 7 in/lb) applied via a calibrated torque wrench to the extruder screw, which directly preloads the internal gears, springs, and drive components of the extruder assembly, thereby altering the mechanical consistency of filament feed. Baseline resistance was measured using a four-point probe configuration to eliminate contact resistance contributions and provide intrinsic conductivity data independent of substrate effects. A fixed torque of 7 in/lb was maintained for all subsequent experiments, isolating print speed, stand-off height, and slice geometry as the primary variables of interest. Using this fixed configuration, line sensors (30 mm length) were printed with a 0.8 mm nozzle onto rigid PEI 1010 substrates (125 × 25 × 2.5 mm) across a comprehensive experimental matrix investigating four print speeds (3, 5, 10, and 15 mm/s) and two layer heights (0.25 mm and 0.35 mm), with at least five replicates per condition to ensure statistical reliability. The fabricated sensor arrays are shown in Figure 1a, and the in-situ deposition process inside the high-temperature chamber is illustrated in Figure 1b. The PEI

1010 substrate was selected for its compatibility with the PEI filament matrix, promoting interfacial adhesion while minimizing substrate-induced sensor deformation during deposition. Electrical contacts were established by applying silver paste pads at the sensor ends, micro-soldering copper wire leads, and encapsulating the junction with a second silver paste layer to minimize parasitic contact resistance. Baseline sensor resistance R_0 was recorded via two-point probe, appropriate given the single-track geometry and integrated contact scheme. To decouple substrate-induced effects from intrinsic material behavior, a parallel set of free-standing fibers was extruded at equivalent speeds (3, 5, 10, and 15 mm/s) without a substrate (Figure 1b). Fiber diameter was measured optically and resistance recorded via two-point probe, providing a reference dataset that isolates extrusion speed effects on conductivity free from nozzle compression and lateral spreading imposed by substrate contact.

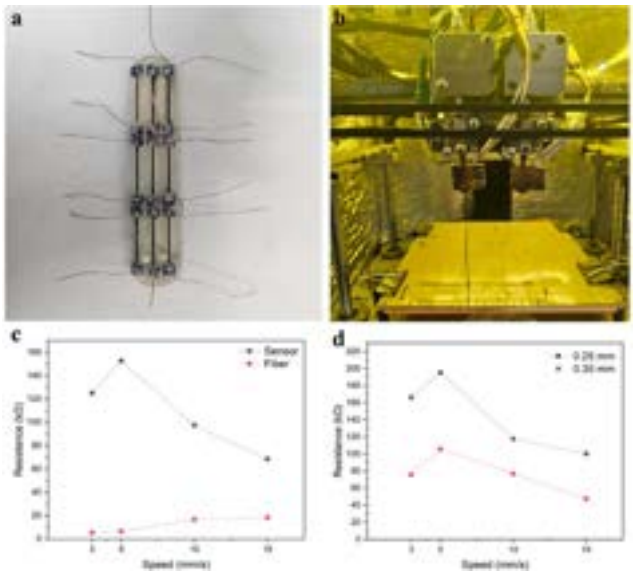


Figure 1. *(a) Fully printed PEI/CNT/CB line sensor elements arrayed on a rigid PEI 1010 substrate; (b) In-situ direct deposition process utilizing the customized high-temperature FFF extruder assembly; (c) Baseline electrical resistance (R_0) of substrate-printed sensors and freely extruded filament beads plotted against extrusion speeds a function of printing; (d) Influence of layer thickness on the baseline electrical resistance (R_0) of the printed sensors.*

3. Results/Conclusions

Substrate-printed sensors exhibited decreasing R_0 with increasing print speed (Figure 1c), consistent with enhanced lateral spreading under nozzle compression that expands the effective conductive cross-section and filler contact density. Freely extruded fibers showed the opposing trend, with resistance increasing monotonically due to mechanical drawdown reducing the strand cross-sectional area (Figure 1c). Critically, free-standing fibers exhibited substantially lower absolute resistance than substrate-printed sensors across all speeds, confirming that these two configurations represent fundamentally distinct process-geometry combinations rather than equivalent material states. Layer thickness further influenced R_0 predictably (Figure 1d): thinner layers imposed greater substrate compression, enhancing carbon network density and filler alignment, while thicker layers reduced it. Collectively, these results confirm that substrate interaction and spatial confinement are the dominant factors governing R_0 in FFF-printed PEI/CNT/CB sensors. Future work will extend this

investigation to varying filler concentrations and different printing temperature to establish comprehensive process–property optimization maps.

Validation of the MUVAX Industrial Concept and FSW Technology Solutions for Fuselage Longitudinal Joints: Results from MRL4 Trials

Marco Pacchione
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1. Introduction / Objectives

The MUVAX project investigates the innovative industrial application of Friction Stir Welding (FSW) for manufacturing longitudinal joints (LJs) in fuselage barrel assemblies. This concept, which utilizes an external welding apparatus, offers significant advantages over riveting, including estimated cost savings and a weight reduction of approximately 1 kg per meter of joint. The primary objective of this phase was to demonstrate the high quality and robustness of this automated shell manufacturing technology and to validate the core technology solutions of the innovative industrial concept. This paper details the work accomplished during the Manufacturing Readiness Level 4 (MRL4) maturation phase, conducted in synergy with the LuFo Kamel partnership, focusing on validating core process building blocks—including edge preparation/milling, welding process capability, and surface grinding feasibility—to establish a robust process window and tool concept.

2. Methodology

The MRL4 maturation phase adopted a rigorous Design of Experiments (DoE) approach to investigate and validate the process building blocks (PBBs) critical to the innovative MUVAX industrial concept. The trials were executed primarily using the FhG-IWS Dresden setup in cooperation with partners such as HEREON and integrated under the LuFo Kamel project, covering three main technology solutions: edge milling, welding, and post-welding surface grinding.

Welding investigation involved tool optimization to improve welding speed (targeting up to 120 mm/min, compared to the state-of-the-art 40 mm/min) and robustness. **Edge milling** aimed to validate the floating milling tool concept to achieve strict thickness tolerances. **Surface grinding** was performed to validate the capability of a robot-mounted grinding concept. The overarching goal of the experimentation was to validate the process window, repeatability, and technical feasibility of these down-selected technology solutions.

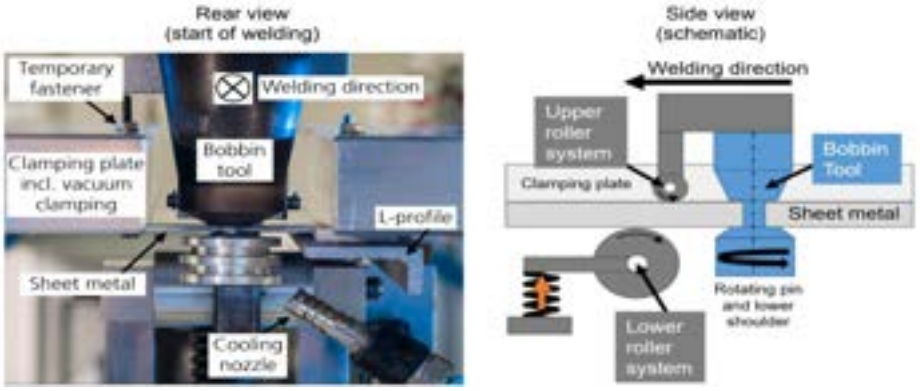


Figure 1. *Friction stir welding in the MUVAX system: rear view at the start of the welding (left), schematic view of the welding tool and roller system configuration (right)*

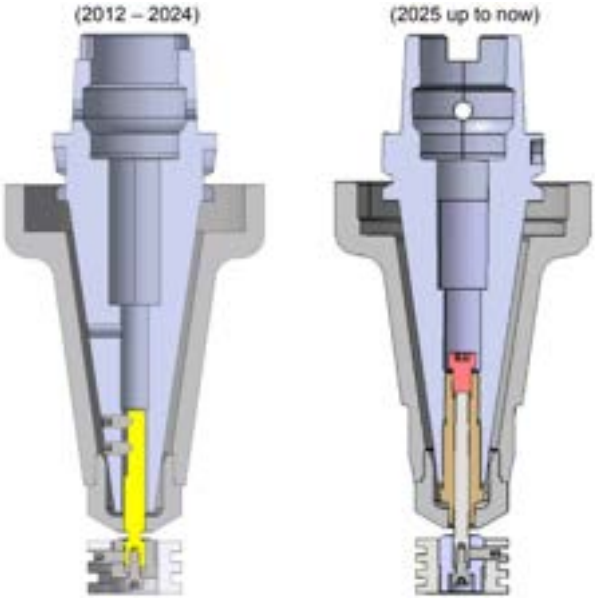


Figure 2. *Bobbin-tool design evolutions*

3. Results / Conclusions

The comprehensive MRL4 experimental campaign successfully matured and technically de-risked the core processes for the MUVAX industrial concept. This culminated in the validation of process capabilities and repeatability. Key results demonstrated the viability of the bobbin tool with an innovative sleeve concept, confirming the technical feasibility of significantly increasing welding speed and tool robustness. Furthermore, the trials demonstrated the capability of the milling process to achieve stricter tolerances and validated the robot-mounted grinding concept. These results lay the foundation for subsequent MRL5 trials at the shell level and validate the technological solutions supporting the projected industrial benefits: a 50% cycle time reduction and substantial cost savings for the longitudinal joints.

Study of the recycling impact on fatigue behaviour of a Ti-6Al-4V produced by SLM

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[2] *UnIRE - Unit for Innovation and Research in Engineering, Portugal*
[3] *UNIDEMI & LASI & CINAV, Portugal*
[4] *NOVA University of Lisbon, Portugal*

1. Introduction / Objectives

The importance of the circular economy has been growing in recent years, influencing how technology is developed. Manufacturing technologies are increasingly aligning with the 4 R principles (Reuse, Reduce, Remanufacture, and Recycle), shifting the paradigm from mass production to highly flexible and customised production . One technology worth mentioning is Selective Laser Melting (SLM), which enables the reuse of powder from previous manufacturing batches . However, the quality of these parts, particularly regarding fatigue, remained largely unexplored. Therefore, the objective of this work is to predict the fatigue behaviour of a Ti-6Al-4V alloy produced by SLM, based on three consecutive reuse cycles.

2. Methodology

Three different batches of Ti-6Al-4V are studied. The first batch was composed of Ti-6Al-4V virgin powders. The second batch was composed of Ti-6Al-4V powder recycled through one cycle of the powder recycling procedure as described by Daniela et al. . Moreover, the third batch was composed of Ti-6Al-4V powder recycled through two cycles of the powder recycling procedure. The manufacturing quality of the specimens was evaluated through Vickers' hardness determined in accordance with ASTM E3-11: 2017 , and the defects intrinsic to the process and the recycling. The quantitative study of the defect area of each batch was performed using an optical microscope and ImageJ. The SN curves were predicted based on the Alves et al. models . To predict fatigue life and relate it to the recycling process of Ti-6Al-4V obtained by SLM, two models were used, one suitable to determine the fatigue limit, σ_w, for a million cycles, based on the hardness and the total area of pore defects found in the specimens . Furthermore, another model based on the fatigue limit for a million cycles, the $\sqrt{area}$ of the largest initial pore and the $\sqrt{area}_{admissible}$ assumed to be 1000 µm as proposed . Both models were developed using Python software, version 3.10.

3. Results / Conclusions)

From the experimental results, the biggest defect area, initial defect size, and the hardness of each of the 3 batches of specimens were obtained. These data were the input values for the two models. It was concluded that the recycled area of the largest defect grows approximately 15% for each batch, and the value of the hardness decreases (between 15% to 11%) as well as the fatigue limit. The hardness value and the largest defect area of batch 3 are higher than those of batch 2, 5,66% and 8% respectively. The fatigue limit difference between batches 3 and 2 is 3,78%.

Figure 1 shows the expected fatigue behaviour for each batch of the Ti-6Al-4V alloy specimens manufactured by SLM. This model compares the predicted fatigue behaviour. Batch 1 was the

one that is expected to perform better when tested to fatigue, with a smaller area of initial defect and higher hardness. It was also observed that the biggest reduction in the expected fatigue resistance is seen for one reuse cycle, since afterwards, batches 2 and 3 showed overlapped S-N curves.

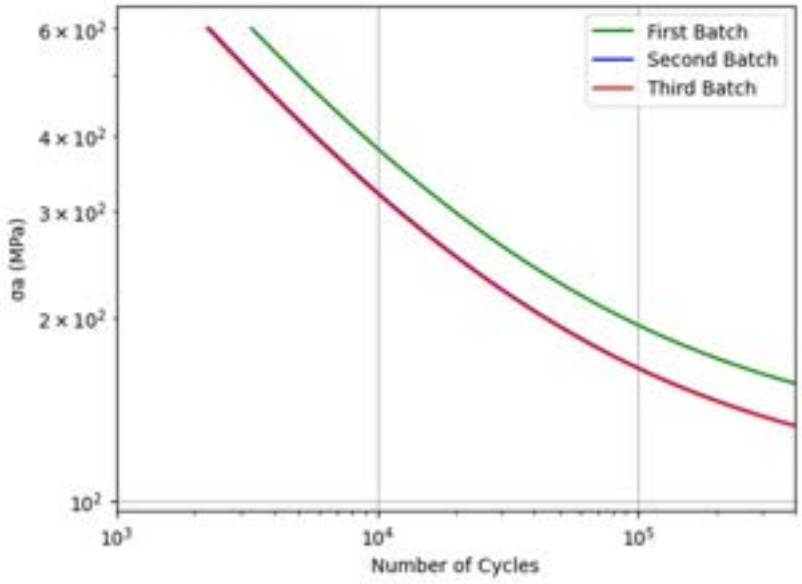


Figure 1. *Predicted S-N curves of the batches with different recycling processes.*

Experimental and Numerical Investigation of the Dynamic Properties of Sandwich Structures with Lattice Cores

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1. Introduction / Objectives

Sandwich-structures, composed of two stiff face sheets and a lightweight core, exhibit very high specific stiffness and are therefore indispensable in aerospace applications. In fiber-reinforced polymer (FRP) composites the core is usually a foam or wood, whereas metallic variants often employ honey-comb or corrugated sheets . Recent progress in additive manufacturing (AM) makes it possible to generate complex core geometries—such as lattice architectures—that can be optimally tailored to specific application requirements. While the static or impact behaviour of lattice cores has been investigated analytically, numerically and experimentally , their dynamic response remains largely unexplored. However, a profound understanding of the dynamic properties of components is of great importance in aerospace, as several effects can lead to dynamic excitation. Therefore, the present work aims to numerically and experimentally investigate how key geometric parameters of a lattice core (unit-cell size, strut diameter) affect the dynamic properties of the entire sandwich plate.

2. Methodology

In the numerical investigation, a finite-element model of the sandwich plate is built. The core of the sandwich structure consists of a body-centered-cubic (BCC) lattice with systematically varied unit-cell dimensions and strut diameters. The face sheets are modelled with shell elements, while each lattice strut is modeled by circular beam elements. The diameter of the beam elements varies for different strut diameters. The simulations employ the isotropic elastic properties of a cured resin that is used to fabricate test specimens for the experiments. An eigenvalue analysis yields natural frequencies and mode shapes that can be compared with the experimental results afterwards. Furthermore, the dynamic interaction between the full sandwich structure and the BCC unit cells is examined. In particular, the investigation focuses on whether coupling effects emerge when the natural frequency of the individual lattice struts approaches that of the overall structure.
Based on the results of the numerical analysis, a series of rectangular sandwich specimens is fabricated by stereolithography (SLA) using a standard photopolymer resin for both face sheets and lattice struts, fig. 1. The unit-cell dimensions and the strut diameters correspond to those used in the simulations. The specimens are excited by a broadband shaker and the frequency response is measrured with a Laser-Doppler vibrometer (LDV) to perform the dynamic characterisation of the sandwich plates. Finally, the numerical and experimental results are compared in order to evaluate the accuracy of the simulation model.

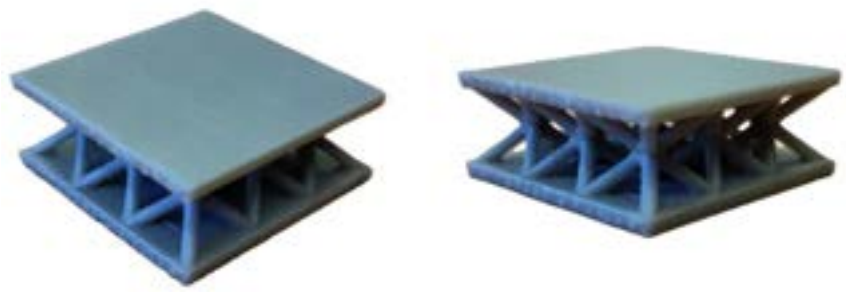


Figure 1. *Example of 3-D-printed lattice core sandwich fabricated by SLA.*

3. Results / Conclusions

The study describes how the geometry of the lattice core influences the dynamic properties of the sandwich structure. In addition, a numerical model of the sandwich—comprising beam and shell elements—is developed and validated by comparison with the experimental investigations. Consequently, future predictions of the dynamic behaviour of sandwich structures with lattice cores can be made using simulations. A precise understanding of these dynamic characteristics can help, for example, to limit the vibrations of the overall structure by adjusting the geometric parameters of the unit cell, thereby actively mitigating noise issues or aging effects.

Study of additive manufacturing of advanced ceramics with acoustic waves

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[2]AITHRA, France

1. Introduction / Objectives

Ceramic are advanced materials used in spatial applications because of their uncommon properties, especially their thermal stability and resistance, to make lighter, smaller or more efficient components while freeing manufacturers from dependency on critical metals. But current manufacturing costs limit ceramics adoption. This PhD takes part of a disruptive process development which simplifies manufacturing to unleash ceramic uses.
Selective Acoustic Sintering (SAS) is a binder-free additive manufacturing process which shapes and densifies ceramic powders in one single step .
A high-power ultrasound beam is focused in a pre-heated powder volume. Sintering occurs in the focal region due to local heating and pressure increase. This focal region is then moved in the powder volume to densify 3D structures.
This technology is inspired by Direct Sound Printing and Spark Plasma Sintering.
The objective of this PhD is to study and improve the process in order to print first ceramic parts.

2. Methodology

Titanium dioxide has been chosen for first sintering trials, and the powder has been characterized with SPS, to understand its sintering behavior. The interaction between powder and ultrasounds has also been studied. An acoustic bench for speed of sound and acoustic attenuation measurement has been set up, which was inspired by the pulser/receiver method found in the literature , . This helps determine the length of the focal region and the heating of the powder in this region, which is linked to the powder acoustic attenuation.
A complete powder pre-heating system has been developed in the SAS machine in order to provide extra energy for the ceramic powder to sinter at the focal region. The powder volume is pre-heated just below its sintering temperature, and the addition of the ultrasound focusing activates the local sintering. Also, a powder compression system has been set up in the machine. Applying pressure on the powder during the sintering cycle helps acoustic transmission and densification, by reducing the powder porosity.
Acoustic pressure in the water-filled crucible has been studied. A hydrophone, moved in the (X,Y) plan of the acoustic region, provided a pressure map to help find the focal region and measure its energy. Sintering trials have been done with the machine complete on TiO2 powder, and parameters as temperature, pressure and displacement path are being studied to 3D print our first ceramic part. Figure 1 shows the pressure map done with the hydrophone measurement in water, Figure 2 shows the temperature and acoustic power evolution during a sintering cycle on the SAS machine.

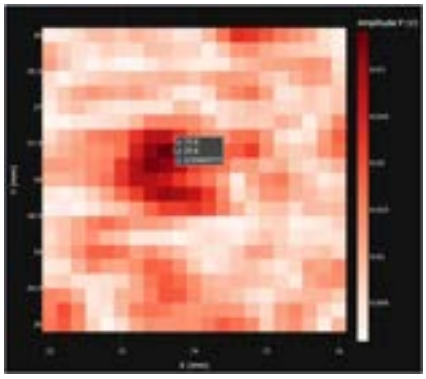


Figure 1. *Pressure map (X,Y) of*

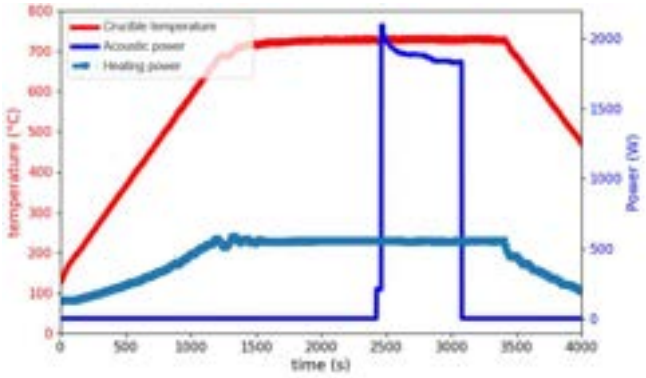


Figure 2. *Temperature, heating power and acoustic power*

3. Results / Conclusions

A complete machine has been developed to reach a powder pre-heating maximum temperature of 1000°C, and an applied maximum pressure of 10 MPa. The heating and compression systems have been patented. Pressure application on the powder has been found to be crucial for ultrasound propagation inside de powder, as well as for densification. The focal region has also been entirely characterized in water. Its diameter is approximately 500 µm, resulting in acoustic pressure of 2 MPa. However, the temperature increase in this region is being measured and is estimated to be the order of 100°C depending on the nature of the powder and its granulometry. Sintering trials have been done on micrometer-size powders of titanium dioxide.

Tensile Characterization of Light-Weight PLA and ASA Thermoplastics for Fused Filament Fabrication

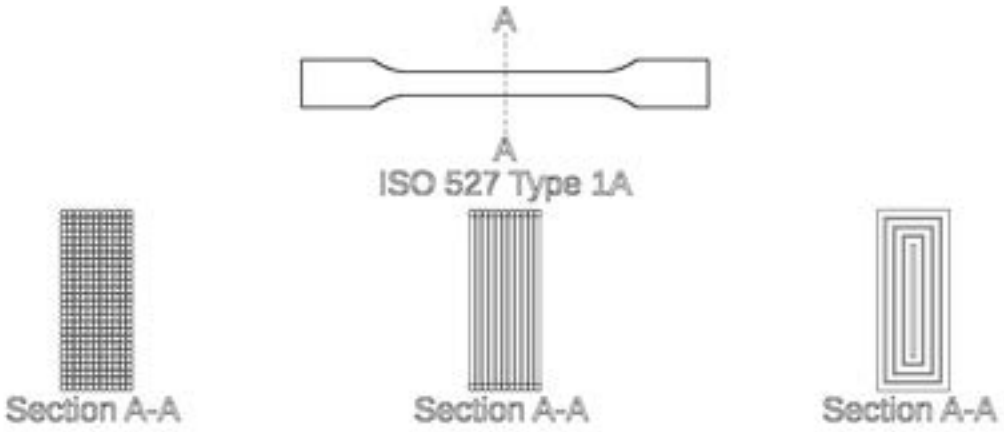
Alexander J Lamey, Ruben E Perez
Royal Military College of Canada

1. Introduction / Objectives

Components manufactured with Fused Filament Fabrication (FFF) exhibit anisotropic mechanical properties which are dependent on print orientation . Studies have controlled the direction of infill to vary the Raster angle to change the mechanical properties of specimens . Research suggests that FFF can be optimized by modifying print direction and orientation to control anisotropy . Such optimizations would prove useful when applied to Uncrewed Aerial Systems (UAS) where FFF is often used for the production of their components . This is due to the ability to manufacture complex geometries and the low price of manufacturing, but some new light-weight materials' properties have yet to be characterized. In this this paper, three light-weight materials, Light-Weight PolyLactic Acid (LW-PLA) , Light-Weight PolyLactic Acid High-Temperature (LW-PLA-HT) , and Light-Weight Acrylonitrile Styrene Acrylate (LW-ASA) are characterized in accordance with ISO 527-1 and ISO 527-2 to determine their anisotropic mechanical properties.

2. Methodology

This paper analyzes additively manufactured ISO 527-2/1A/1 specimens. Three unique orientations are tested: in-line (E_1), in-plane (E_2), and out-of-plane (E_3). Thirty specimens for each material are tested, 10 for each orientation shown in Figure 1. A total of 5 specimens are used to determine the tensile behaviour of the material and another 5 to determine the Poisson's ratio for each direction. All testing for the determination of mechanical properties is performed on an Instron 3367 Tensile Testing Machine using an Epsilon model 3542 extensometer. Determination of the Poisson's ratio of each specimen is accomplished through the use of digital image correlation using a Schneider Kreuznach JADE 2.8/35 C-Rn and a 0.66mm dot size speckle pattern. Test specimens are 3D printed using FFF with the cross sections shown in Figure 1, with all materials preconditioned to 10% humidity before manufacturing. The E_1 and E_2 specimens, shown in Figures 1a and 1b respectively, are printed with 100% rectilinear infill aligned longitudinally and laterally, respectively. Both E_1 and E_2 specimens have 1 perimeter to maximize the contribution of the directional infill while maintaining the external tolerance to ISO 527-2. However, the E_3 specimens, shown in Figure 1c, are printed such that the entirety of the build-path is perimeters to independently test the inter-layer bonding. The E_3 orientation is unstable during manufacturing due to the vertical print orientation, and therefore uses a support to brace the test specimen during printing. This support is removed prior to testing and sanded flush to the dimensions detailed within ISO 527-2. All Type 1A specimens are printed with a 2mm brim to prevent bed-separation, which are subsequently post-processed to meet dimensional requirements. The data collected in accordance with ISO 527-1 includes stress vs. strain curves, tensile modulus, Poisson's ratio, tensile



a) E_1 **b)** E_2 **c)** E_3

Figure 1. *Tested Cross Sections for a ISO 527/1A/1*

3. Results / Conclusions

In this paper, the mechanical properties of additively manufactured LW-PLA, LW-PLA-HT, and LW-ASA in 3 orientations, in-line, in-plane, and out-of-plane, are determined for the design and manufacturing of UAS components or other applications. The anisotropic behaviour of FFF is quantitatively captured through the testing of specimens for each material in each

orientation. A detailed comparison between the experimentally determined mechanical properties of the tested materials is performed herein. The mechanical properties of the tested materials are practically useful for understanding the tensile loading response in FFF UAS or other applications where high mass is an inhibiting factor.

Structural Integrity of Solid-State Metal Additive Manufacturing for Aerospace Components

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Worcester Polytechnic Institute, USA

1. Introduction / Objectives

Solid-state additive manufacturing (SSAM) of metals by processes such as cold spray (CS) and additive friction stir deposition (AFSD) are emerging as attractive alternatives to fusion-based methods for aerospace structural components due to their elimination of solidification defects, improved feedstock flexibility, and potential for high deposition rates. However, their structural integrity is governed by process-specific microstructural features, including interparticle bonding, defect populations, and residual stress evolution, which constrain their mechanical properties and usable lifetimes. By integrating studies on CS Al 6061 and AFSD Ti-6Al-4V, the objective of this work is to develop process parameter – microstructure – mechanical property linkages and guidance for structural design and repair applications in aerospace systems.

2. Methodology

Two processes, cold spray and additive friction stir deposition, were investigated to evaluate structural integrity under service-relevant conditions. Cold spray Al 6061 depositions, Figure 1, were fabricated as both free-standing bulk materials and coatings on substrates. Fatigue behavior of bulk depositions was characterized by systematic SN and long fatigue crack growth testing to assess the role of particle-particle bonding on crack initiation and propagation behavior. Small fatigue crack growth tests on coated specimens were performed to evaluate deposition-substrate interface stability and resistance to spallation in repair configurations.

Additive friction stir deposition Ti-6Al-4V builds, Figure 2, were fabricated at varied build chamber oxygen levels to investigate the role of environmental exposure on mechanical properties. Builds were first characterized by large-area elemental, residual stress, and microstructural mappings. Tensile, Charpy impact, and SN fatigue mechanical test coupons were prepared from the builds to quantify the variation of properties with build chamber oxygen content between builds and spatially within individual builds.



Figure 1. *Cold spray Al 6061 builds used for bulk SN and fatigue crack growth testing.*

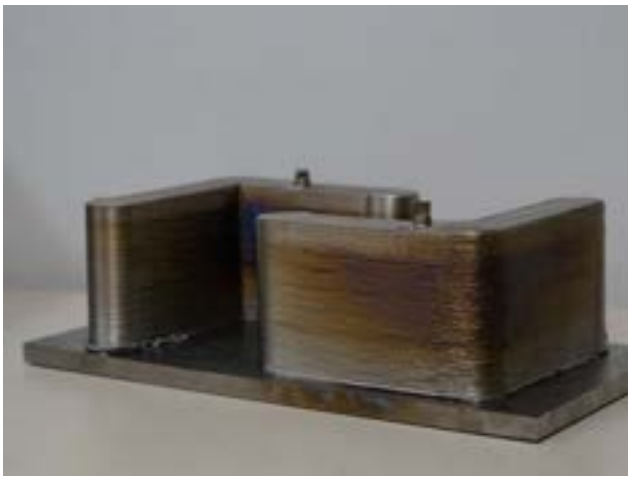


Figure 2. *Additive friction stir deposition Ti-6Al-4V builds used for composition, residual stress, microstructure, and mechanical property mapping.*

3. Results / Conclusions

Results demonstrate that structural integrity in SSAM is governed by the interplay between defect populations, residual stress fields, and microstructure. In as-fabricated CS Al 6061, fatigue life is strongly controlled by crack initiation at intrinsic defects associated with interparticle bonding, while robust interparticle bonding following heat treatment enhances resistance to crack propagation. In AFSD Ti-6Al-4V, fusion defects and significant macro-scale residual stresses are largely absent following adequate processing parameter selection. Mechanical properties are instead strongly governed by microstructural and elemental gradients within the builds. A unifying insight is that both processes rely on optimized solid-state bonding and controlled microstructural and defect populations to achieve structural integrity. The combined findings enable development of manufacturing guidelines that support the deployment of SSAM technologies in aerospace structural and repair applications.

Transforming CS-23 Aviation: Flying Testbeds, Sustainable Propulsion and Regional Air Mobility Concepts

Chaired by:
Dr. Sebastian Spitzer (TU Dresden, Germany)

Battery System Development to Empower Electrified Aviation Within OST4AVIATION

Florian Franke, Alperen O. Altun, Maurice L. Dörnte, André Vetterlein, Stefan Kazula
German Aerospace Center (DLR), Germany

1. Introduction

Batteries are a promising energy carrier for electrified aviation not only for powering aircraft propulsion systems but also for supplying aircraft subsystems . The main limitation for the widespread implementation of batteries as energy carriers in electrified aircraft is their gravimetric energy density . Especially on system level, the mass and volume overheads resulting from the battery management system (BMS), the thermal management system (BMS) or the required safety features deteriorate the energy density. However, the individual design features of the battery system affect each other and could therefore be combined advantageously, for example when the TMS for battery cooling during regular operation is also used to support an emergency cooling system dedicated to thermal runaway (TR) scenarios . Hence, the goal of this study is to present the key design features and their promising combinations to ensure compliance with airworthiness requirements while at the same time maintaining a high energy density.

2. Methodology

For a systematic description of the key design features and their mutual interference, the battery system development method according to Figure 1 is elaborated. The used approach of the V-model connects the system design and model generation from the branch on the left-hand side with the system integration and validation from the branch on the right-hand side. The level of detail increases from top to bottom. The full paper will describe the interference between the sub-systems and the components. As an example, the electric sub-system encompasses the stack of cells as the energy carrier, the BMS for control and the bus bar, wires and connectors for current transmission . Within this electric sub-system, the behavior of the cells is influenced, among many other factors, by the balancing strategy of the BMS . The cells are also affected by the other sub-systems, for example by the temperature level of the coolant provided by the TMS. However, also higher system levels have an effect. For instance, the mission profile of the aircraft and the propulsion system architecture dictate the current load. These exemplary influencing variables of balancing strategy, temperature level and current load, should by analyzed with a cell model and validated by appropriate cell cycling tests on component level, sub-system level and system level.

Besides degradation of the properties of the cells, also the risk of TR has to be taken into account. The battery system must ensure cell-to-cell non-propagation when a single cell experiences TR. Moreover, continued safe flight and landing should be achieved by containment of the TR event even in case of multiple cell TR scenarios . Suitable experimental tests for regular operation and for abuse conditions will be described in the full paper for the different levels of the V-model.

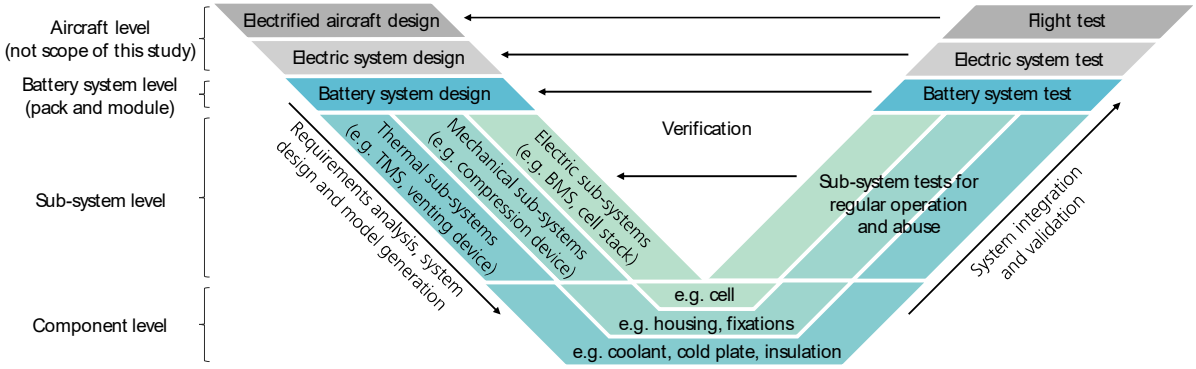


Figure 1. *Simplified proposal for a battery system development method in relation to the V-model of the VDI-guideline 2206.*

3. Conclusions

The study elaborates a development method for battery systems. The method is then used to highlight the key design features and their promising combinations for aircraft application. Therefore, promising concepts of battery sub-systems and components are exemplary described and their mutual interference is discussed. Additionally, appropriate experimental set-ups for regular operation tests and abuse condition tests are presented for the different levels of the V-model. Thereby, this study addresses the battery-related research topics of the DLR – German Aerospace Center within the OST4AVIATION ecosystem. The results provide guidance for future studies on aircraft battery systems to empower electrified aviation.

Efficient Preliminary Design and Analytical Pre-Dimensioning of Design-Space-Adapted Hydrogen Pressure Tanks for Future Fossil-Free Aviation at the Example of a Cessna 172N

Sebastian Spitzer, Edwin Zimmerman, Alexander Koepp, Chris Fischer, Johannes Markmiller, Maik Gude
TU Dresden, Germany

1. Introduction and Objectives

The aviation industry is undergoing a transition toward fossil-free propulsion technologies, with hydrogen emerging as a promising energy carrier due to its high gravimetric energy density. However, the integration of hydrogen storage systems into existing aircraft structures poses significant challenges, as current design methods are predominantly tailored to cylindrical pressure vessels, leading to suboptimal utilization of available installation spaces. This study introduces a methodology for the efficient preliminary design and analytical pre-dimensioning of design-space-adapted Type-IV hydrogen pressure tanks. The approach focuses on maximizing volumetric efficiency while ensuring manufacturability and structural compatibility. The methodology is demonstrated using the Cessna 172N as a reference aircraft, showcasing its potential to support the transition to sustainable aviation.

2. Methodology

The proposed methodology integrates a systematic workflow, starting from installation space identification and measurement to geometry processing and automated variant computation. The process begins with the selection and measurement of potential installation spaces within the Cessna 172N, including the forward and aft baggage compartments and the cabin area with the rear bench removed. A Python-based analytical pre-dimensioning model is employed to transform a rotationally symmetric inner tank contour into a manufacturable filament-wound layup. The model incorporates an isotensoid reference state as the target for fiber orientation and thickness distribution, while a winding simulation ensures compliance with manufacturing constraints, such as limited fiber steering and layer thickness tolerances.

The methodology accounts for critical integration constraints, including structural clearances, mounting requirements, and accessibility for inspection and maintenance. Variants are evaluated based on key performance indicators, such as stored hydrogen mass, system mass, gravimetric and volumetric storage efficiencies, and mission-specific range estimates. A weighted multi-criteria assessment is used to balance trade-offs between range potential, integration effort, and usability.

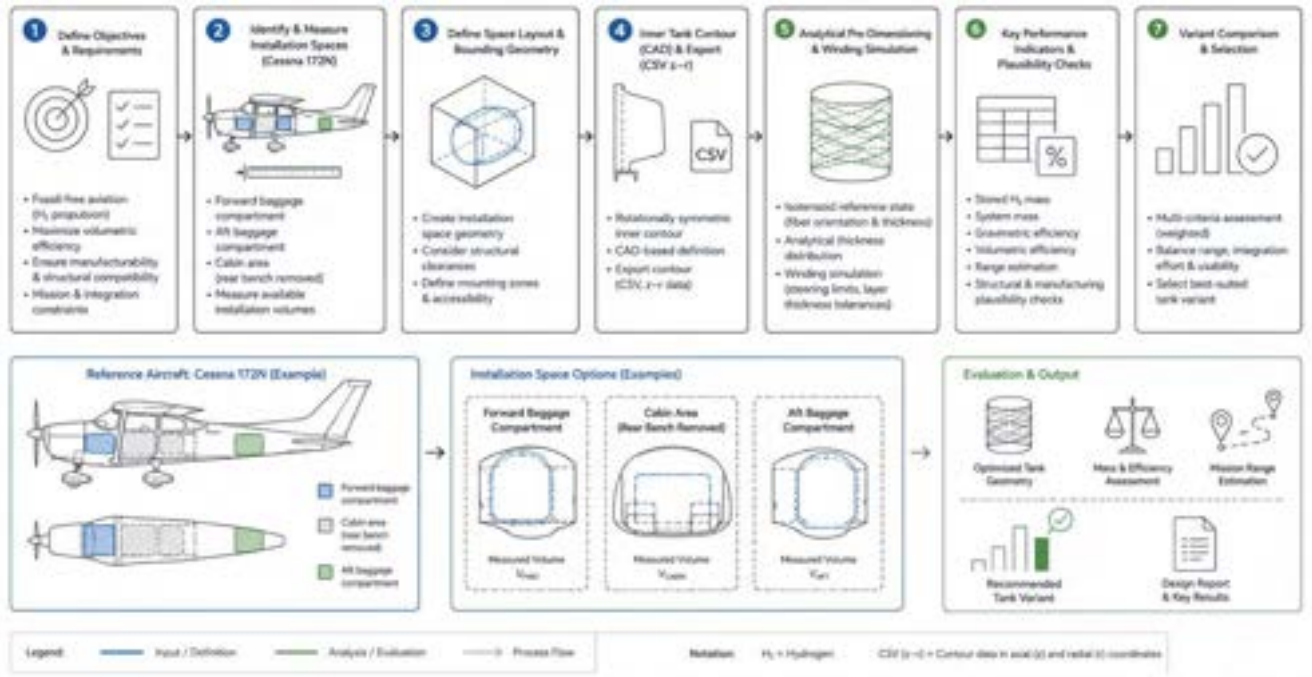


Figure 1. *Workflow for the development and evaluation of design-space-adapted hydrogen pressure tanks.*

3. Results and Conclusions

The methodology was applied to nine tank variants, demonstrating its capability to address the trade-off between range potential and integration compatibility. Compact designs without rear bench removal achieved hydrogen storage capacities of up to 4.1 kg, enabling ranges of approximately 96.6 km (internal combustion engine) or 102.0 km (fuel cell). Larger designs with the rear bench removed stored up to 16.1 kg of hydrogen, extending the range

to 375.7 km. The results highlight the importance of balancing volumetric efficiency and integration constraints, with the forward baggage compartment emerging as a favorable integration space. The study concludes that the proposed methodology provides a robust framework for the early-stage design of hydrogen storage systems, supporting the development of sustainable aviation solutions.

Model based approach to optimize air stoichiometry and operating pressure for a PEM fuel cell based propulsion system of a four seater aircraft

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1. Introduction / Objectives

Fuel cell performance strongly depends on operating parameters such as stoichiometry, pressure, temperature, and relative humidity. For aviation applications, these parameters must be optimized to maximize overall propulsion system efficiency. In proton exchange membrane fuel cell (PEMFC) propulsion systems, the cathode air compressor constitutes the largest source of parasitic power consumption. Although increasing cathode pressure and air stoichiometry improves stack efficiency, it simultaneously increases compressor power demand, resulting in a trade-off that requires optimization. Furthermore, the optimal operating parameters vary with stack power demand and aircraft altitude due to changing ambient pressure conditions and compressor operating characteristics. This study presents a coupled PEMFC stack and compressor model used to perform parametric investigations under varying operating conditions. In addition, different compressor sizes are analyzed to evaluate the influence of compressor sizing on system efficiency, operating behavior, and feasible operating range while accounting for compressor limits and efficiency characteristics.

2. Methodology

The presented model was developed in MATLAB/Simulink and consists of a semi-empirical proton exchange membrane fuel cell (PEMFC) stack model coupled with a cathode air supply compressor model. Since the fuel cell stack consists of multiple identical cells, the behavior of a single cell was modeled and subsequently scaled to stack level. The fuel cell model was calibrated and validated using published manufacturer polarization curve data for different operating pressures, as illustrated in Figure 1, resulting in an average deviation of 0.2564% between simulation and reference data.
The compressor model is based on aerodynamic and thermodynamic equations describing pressure ratio and compressor power demand. Compressor operating limits and isentropic efficiency characteristics were implemented using compressor maps. A parametric study varying cathode air stoichiometry and stack inlet pressure was conducted using cross-combinations of net power demands, flight Mach numbers, and flight altitudes representing the complete flight mission profile from take-off, climb, cruise and descent conditions.
In an initial optimization step, compressor limits were neglected and a constant compressor efficiency of 75% was assumed to derive compressor-independent optimal operating parameters. The resulting operating ranges for corrected air mass flow and pressure ratio were then used to identify suitable compressor characteristics. Since no compressor fully covered the complete operating range without surge or choking limitations, a compressor

providing sufficient coverage from cruise to take-off conditions while maintaining high efficiency near the desired operating points was selected.

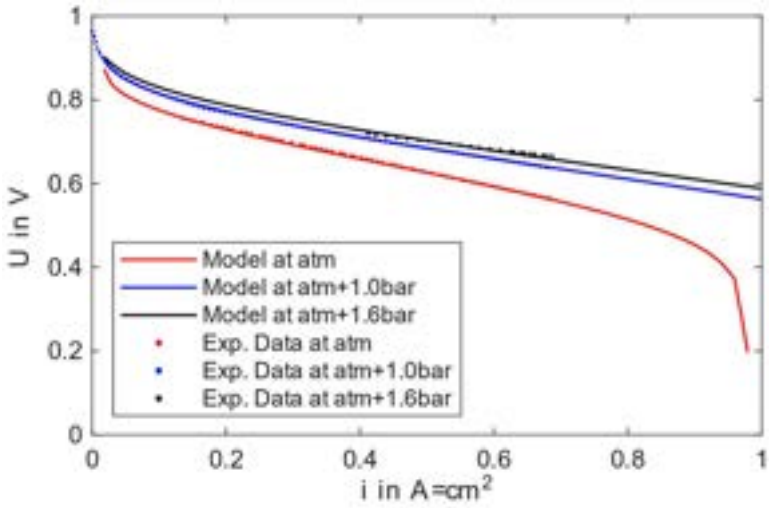


Figure 1. *Polarization curves of the model compared to manufacturer data of the PowerCell P-Stack*

Subsequently, compressor operating limits and map-based compressor efficiency characteristics were included to evaluate their influence on optimized operating parameters and overall propulsion system behavior. Different compressor sizes were additionally investigated by scaling the compressor maps. Finally, complete mission simulations were performed for all investigated configurations, including a reference operating strategy. The mission profile was additionally extended to determine the maximum achievable aircraft range for a fixed hydrogen tank capacity. The complete methodology was repeated for a turbine-assisted architecture utilizing cathode exhaust energy to partially drive the compressor, thereby reducing parasitic compressor power demand and altering the resulting optimal operating parameters.

3. Results / Conclusions

The results show that lower cathode air stoichiometry generally increases overall system efficiency, as the stack efficiency gain at higher stoichiometry does not compensate for the increased compressor power demand. Increased air stoichiometry is only beneficial at very low stack loads to maintain stable compressor operation and avoid surging. Higher stack inlet pressure is advantageous primarily at high load conditions, where fuel cell efficiency gains become more significant. Optimization of both operating parameters increases flight mission averaged system efficiency by up to 1.5 – 2 % while accounting for compressor operating limits, resulting in a maximum aircraft range increase of approximately 50 – 70 km (5 – 9 %) for a constant hydrogen tank capacity. Furthermore, smaller compressors maximize mission averaged efficiency and range, as cruise conditions dominate the mission profile. A turbine-assisted architecture further improves efficiency and range; however, condensation-related turbine degradation and efficiency losses require additional investigation.

Investigation of CO2-neutral propulsion concepts in the preliminary design for a general aviation aircraft

Johanna Haug, Annika Staats, Andreas Bardenhagen
Technische Universität Berlin, Germany

1. Introduction / Objectives

Due to its reliance on fossil fuels, the aviation industry contributes significantly to global CO_2 emissions . The objectives outlined in Flightpath 2050 indicate the need for alternative propulsion concepts. General aviation represents a suitable platform for initial investigations due to its comparatively manageable technical complexity and financial requirements. As a scalable test environment, it enables the development, evaluation, and validation of alternative propulsion systems. Therefore, the objective of this study is to comparatively investigate the application of different CO_2-neutral propulsion concepts for a CS-23 aircraft designed to accommodate nine passengers with a range of 500 NM. The work is conducted in cooperation with APUS ZeroEmission GmbH and using the aircraft design software Desmo developed by Pace Aerospace Engineering & IT GmbH.

2. Methodology

Three aircraft configurations are considered for a defined mission task including fuel reserves and performance requirements. Two of the configurations feature low-temperature proton exchange membrane fuel-cell-based propulsion systems, one using cryogenic hydrogen and the other using compressed hydrogen as the energy carrier. The third configuration is equipped with a turboprop propulsion system powered by sustainable aviation fuel. To simplify the aircraft design process, fixed configuration parameters are applied across all concepts. These include configurational aspects such as a conventional low-wing, twin-engine layout with nacelle-mounted engines, a conventional tail arrangement, as well as geometric parameters such as fuselage dimensions and fixed tail volume coefficients. The fuel system is integrated into the wing structure where possible and otherwise located in the nacelles.

The estimation of mass properties, geometry, center of gravity, and aerodynamics is mainly based on empirical and semi-empirical methods and assumptions from Torenbeek , Raymer and Roskam . Propulsion system performance is modelled using performance maps from Desmo. Constant efficiencies are assumed for the electric motor, inverter, and DC/DC converter in the fuel cell system. The mass of the fuel cell propulsion system is estimated based on mass-to-power ratios derived from manufacturers' datasheets, with the component masses scaled according to the required power output. The aircraft configurations are developed using the graph-based calculation approach implemented in Desmo.

Individual sub-models are validated through the re-modelling of a King Air 200-series aircraft including calibration of both the aerodynamic and turboprop models. The validation results show that most of the assessed models achieve sufficient accuracy, while the modelling of single-engine climb performance is identified less accurate.

3. Results / Conclusions

The results show that only the turboprop configuration fulfills all mission requirements. The liquid hydrogen variant remains feasible at a reduced range of up to 11.3 NM, while the compressed hydrogen variant does not achieve a usable range. Compared to the

turboprop variant, the advantages of the liquid hydrogen configuration are its CO_2-neutral operation and higher cruise efficiency. However, the liquid hydrogen aircraft exhibits significantly higher maximum take-off mass, overall aircraft dimensions and drag coefficients resulting from the nacelles, cooling air inlet and lateral trim. The primary drivers of maximum take-off mass are identified as the gravimetric power density of the propulsion system and the gravimetric energy density of the tank system. Reducing propulsion system mass to 63 % of the current value would enable a feasible fuel-cell-powered liquid hydrogen aircraft. As the results are based on simplified and partially unvalidated assumptions, they should be interpreted with caution.

Sensitivity of a fuel-cell battery hybrid energy system to commuter aircraft mission profile parameters

Pascal Albrecht, Lukas Schnörer, Dominik Murschenhofer
German Aerospace Center (DLR), Germany

1. Introduction / Objectives

Electrification of commuter routes is of particular interest to airlines, since they require mostly limited range and payload while at the same time offering limited profit margins with conventional combustion engine-based aircraft . Consequently, many projects aim to develop electric aircraft for this market, since they would reduce both climate impact and fuel costs . Depending on the mission requirements, an energy system based on batteries, hydrogen fuel cells or a combination of both in a hybrid electric system would be preferable . In the present study, a sensitivity analysis for an all-electric retrofit of a Cessna 441 commuter aircraft is performed, to determine which input parameters primarily drive the optimal design characteristics of the hybrid energy system. This enables to identify optimal degrees of hybridization for various mission profiles, depending on the selected input criteria.

2. Methodology

The sensitivity analysis is based on statistical design of experiment methods. For each combination of input parameters an energy system design workflow is executed to determine the required energy system size. An overview of the design workflow and the underlying simulation tools is given in **Figure**.

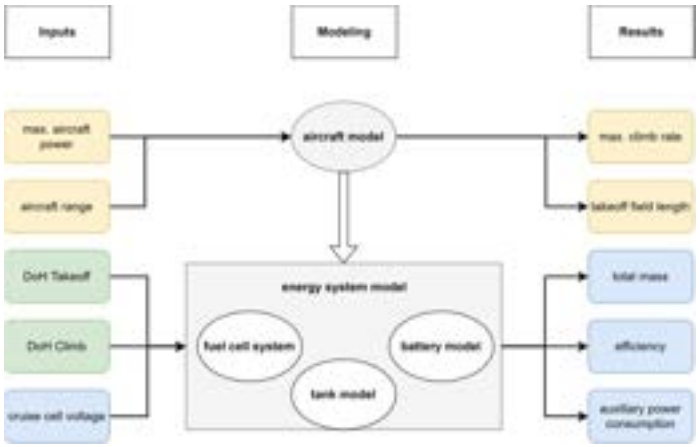


Figure1. *Overview of the study setup and the energy system design workflow.*

The selected inputs can be separated into mission parameters (maximum aircraft power and maximum range), hybrid powertrain parameters (degree of hybridization (DoH) during the takeoff and climb segments) and energy system parameters (target fuel cell voltage during cruise). From the mission parameters, the required electrical power profile for a given flight trajectory is obtained by an aircraft model parametrized to simulate a commuter aircraft based on a Cessna 441. The power profile is then split into power requirements for the fuel cell system and the battery system, considering powertrain efficiencies and the selected DoHs for takeoff and climb. Based on these requirements and the target fuel cell voltage during the cruise segment, the size and operational parameters of the hybrid energy system is evaluated using a fuel cell , a tank and a battery model . The simulation models are fitted with measurement data obtained with in-house fuel cell and battery testbenches . Finally, the results of the design workflow are evaluated based on a set of aircraft performance parameters (takeoff field length and climb rate) and energy system parameters (mass, efficiency and auxiliary power consumption).

3. Results / Conclusions

The evaluation of the sensitivity analysis highlights which inputs and design restrictions affect which output parameter of the resulting design. Moreover, the influence of the mission range, the installed power and maximum energy system mass restrictions on the optimal hybridization factor between fuel cell and battery power can be demonstrated. Preliminary results show, that reducing the maximum aircraft power to maintain the maximum takeoff mass, limits the minimum takeoff field length and the maximum climb rate, requiring some compromises on the aircraft operation with full payload compared to the combustion reference. Similarly, the mission range affects the optimal DoH due to the lower specific energy of the batteries. The results allow evaluating the relevance of the design restrictions and potential future improvement needs. Based on the mission requirements, different hybridization options and design criteria for similar aircraft can be deducted.

Towards New Algorithms for Multidisciplinary Design Optimization (MDO)

Chaired by:
Prof. Joseph Morlier (ISAE-SUPAERO, France) & Prof. Nathalie Bartoli (ONERA, France)

Reliability-based Overall Aircraft Design using GEMSEO

Matthias De Lozzo, Nicolas Roussouly, Olivier Sapin
IRT Saint Exupéry, France

1. Introduction / Objectives

Multidisciplinary analysis and optimisation (MDAO) is becoming increasingly popular in engineering, particularly in the aerospace industry. There is a wealth of supporting literature and dedicated software available, including the open-source Python library GEMSEO® (www.gemseo.org). Furthermore, reliability analysis and reliability-based optimisation techniques are widely used in the structural mechanics community in the presence of uncertainties. The aim of this work is to build a bridge between these two fields. It proposes a methodological and software framework for reliability-based MDAO. The primary objective is to assist MDAO engineers in transitioning from a deterministic to an uncertain environment. The secondary objective is to facilitate the integration of uncertainty quantification techniques, from reliability analysis (RA) to reliability-based MDO (RBMDO), including reliability-oriented sensitivity analysis (ROSA). This work builds on recent developments in GEMSEO.

2. Methodology

GEMSEO is a library for posing and solving multidisciplinary problems, starting with MDO problems. extended it to address MDAO problems under uncertainty. Sources of uncertainty may include model parameters as well as design variables. Switching between these problems is seamless for the user. GEMSEO also offers other uncertainty quantification (UQ) features, such as sensitivity analysis techniques. This work extends these techniques to the field of reliability where the statistics are probabilities. Reliability analysis methods, e.g. Monte Carlo, first-order reliability method (FORM) or importance sampling, are used to estimate these probabilities from an MDA. When the probability is a concern, a ROSA study can be conducted to identify the sources of uncertainty that contribute most to it, using specialized Sobol' indices or target HSIC indices , for example. Finally, we can aim to find the design that minimizes an objective function subject to probabilistic constraints. This is the purpose of RBMDO. All of these steps can be easily chained using the GEMSEO software.
This methodology is illustrated using an overall aircraft design (OAD) problem. The goal is to minimize the maximum take-off weight with respect to the wing area, the wing aspect ratio and the engine sea level static thrust. The problem includes eleven disciplines, representing physics, components and mission phases. These disciplines are available in the open-source Python library gemseo-oad-training , and Figure 1 illustrates their coupling structure. The design is subject to general constraints, such as maximum take-off field length, approach speed and wing span, and minimum vertical velocity margin. The problem also involves uncertain technological readiness parameters and the uncertain gravimetric and volumetric

indices of the liquid hydrogen tank.
We adopt the following experimental protocol based on the methodology outlined above. First, we perform a ROSA study assuming that the variables are independent and compare the results obtained with the Sobol' and HSIC techniques. Then, we model the dependency between the gravimetric and volumetric indices using a copula and study its impact on the results of the HSIC methods. Finally, we compare RBMDO against the standard MDO approach with margin-augmented constraints.

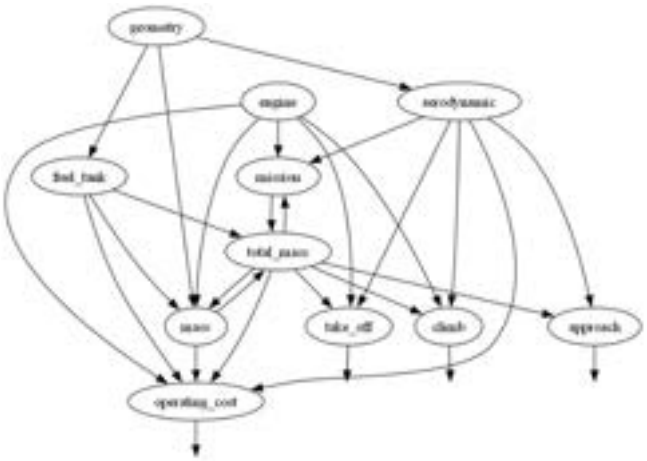


Figure 1. *Coupling graph of the disciplines used in the OAD problem, with a cycle between mission, total mass and mass.*

3. Results / Conclusions

The proposed methodological and software framework aims to facilitate the use of reliability techniques in a multidisciplinary context. An OAD problem subject to technological uncertainties supported its validation. This framework extends the open-source software GEMSEO with new UQ techniques, e.g., ROSA and RBMDO. Some sampling methods for statistics estimation make use of surrogate-based variance reduction techniques developed by the authors . These new developments will enable engineers engaged in multidisciplinary simulation to easily adapt their processes to account for uncertainties and, in particular, to manage critical events.

Surrogate-accelerated co-design of wing and active flutter controller under CS-25 and uncertainty

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1. Introduction / Objectives

Aeroelastic wings are typically sized sequentially: the structure is frozen first, and a flutter-suppression controller is implemented afterwards. Lighter wings flutter sooner and benefit

from active stabilisation , but the structural sizing and the feedback law are tightly coupled and leave mass on the table when treated apart. This study co-designs both for a Goland-style wing (2-DoF) with a trailing-edge control flap, simultaneously satisfying three CS-25 requirements: 629(b) flutter margin, 341(a) discrete-gust loads, and 629(a) general aeroelastic stability. This work goes beyond the current state of the art in three ways: (1) all three certification clauses enter the MDO loop as in-the-loop constraints rather than post-hoc checks; (2) a Kriging surrogate of the open-loop flutter speed accelerates each sub-problem so that the entire Pareto front is recovered in seconds; (3) compliance is then re-evaluated probabilistically against structural properties, controller authority, and atmospheric uncertainty.

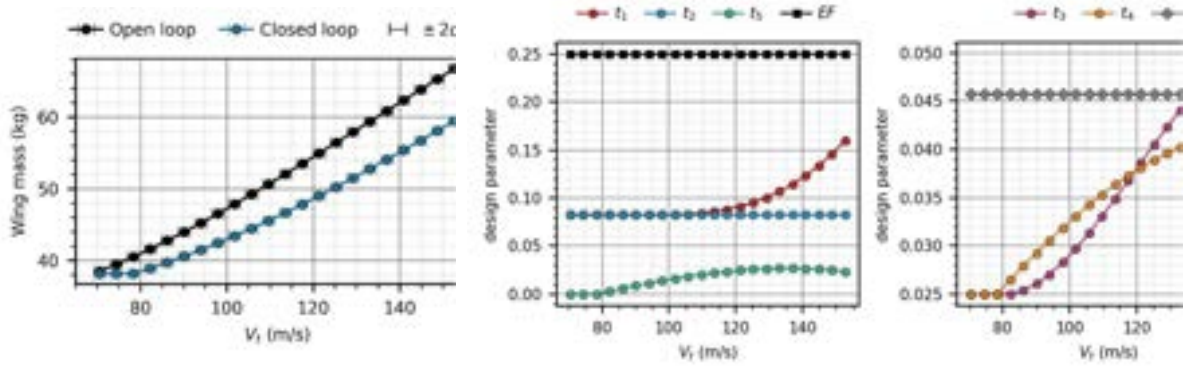
2. Methodology

The structural model is a thin-walled torsion box with six segmen3ts (*Fig. 1*). Five plate thicknesses ($t_{1\ldots5}$) and the flap thickness (t_f) and chord fraction EF form the structural variables. Five LQR gains act on the pitch-plunge-flap states. Unsteady aerodynamics use Glauert flap derivatives $CL_\beta(EF)$, $Cm_\beta(EF)$, shared by every stage of the study.

The Pareto front is traced by a two-pass direct-transcription NLP, implemented in Python with CasADi/IPOPT. The open-loop pass is solved at a series of target flutter speeds V_t (the §25.629(b) margin). Each solve returns one (mass, V_t) point of the structural Pareto front. The closed-loop pass warm-starts from each open-loop design and adds the five LQR gains. The Riccati gain is scheduled at the CS-25 design speeds V_B (maximum-gust intensity), V_C (cruise) and V_D (dive), plus V_t itself, so that the controller is continuous across the full certification speed ladder.

A Kriging surrogate, built with the SMT library, replaces the per-iteration eigenvalue solve. It maps the six design variables – five plate thicknesses and the flap chord fraction EF – to the open-loop flutter speed. The surrogate is trained on a Latin-hypercube sample of the design box, with each sample evaluated using the full eigenvalue model. The same surrogate is called in both passes, acting as the §25.629(b) margin in the closed-loop. Ten-fold cross-validation gives $RMSE \approx 0.5\ m/s$ and $R^2 \approx 0.999$. Outliers beyond 5 median absolute deviations of the median flutter speed are filtered out. A safety pad equal to twice the worst-fold cross-validation residual is added to every V_t target, keeping the surrogate-driven optimum feasible on the direct eigenvalue model.

Each design is then re-simulated against §25.341(a) for the full CS-25 1-cosine gust family at V_B, V_C and V_D. At V_t a quadratic Lyapunov stability proof is computed. The §25.629(a) stability and control requirements under structural deformation are then checked at multiple gust gradients. Compliance under uncertainty is finally evaluated by Monte Carlo sampling, and pairwise attribution identifies the main drivers.



(a) (b)

Figure 1. *(a) Mass-target-speed Pareto for the open and closed loop architectures, accounting for the Kringing (KRG) surrogate propagated uncertainties, and (b) strucutral decision variables progression across the target speeds*

3. Results / Conclusions

The Kriging-accelerated framework recovers the full structural Pareto front in seconds. Wing mass grows near-linearly from 46 kg at the V_B driven lower anchor to 67 kg at the upper closed-loop flutter target, at roughly 0.4 kg per m/s of added margin. Across the front, the LQR feedback law saves between 8.6% and 11.9% of wing mass over the open-loop optimum, the saving growing monotonically with V_t. The flap chord fraction is consistently driven to its upper bound, indicating that the active flap acts as a structural lever rather than purely a control surface. Every Pareto point satisfies §25.629(a), §25.629(b) and §25.341(a) under nominal parameters. Under uncertainty, probabilistic compliance remains above the targeted level, with controller authority and gust intensity emerging as the dominant drivers. The study demonstrates how co-optimising the flight controller and the wing structure simultaneously can yield lighter aeroelastic aircraft that may remain CS-25 compliant under uncertainty.

Preliminary Sizing of Multirotor Platforms for Optimal Mission Planning

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1. Introduction / Objectives

While multiple direct operating cost models have been developed for commercial aircraft, there is a lack of a top-level operating cost evaluation for fighter aircraft suitable for conceptual design. Especially in early stages when the lack of information regarding on-board and mission systems do not allow for a bottom-up approach. The objective is to provide a computationally cheap semi-empirical equation for the hourly cost of fighter operation based on relatively updated data.

2. Methodology

Using data from governmental and industrial sources , a dataset is digitalized and reconstructed using the average cost per flying hour divided by Operating & Support (O&S) and maintenance (Fig. 1). The values are corrected for inflation using the Consumer Price Index (CPI) to use constant fiscal year 2026 dollars. This was complemented with the aircraft's top level design parameters obtained from.

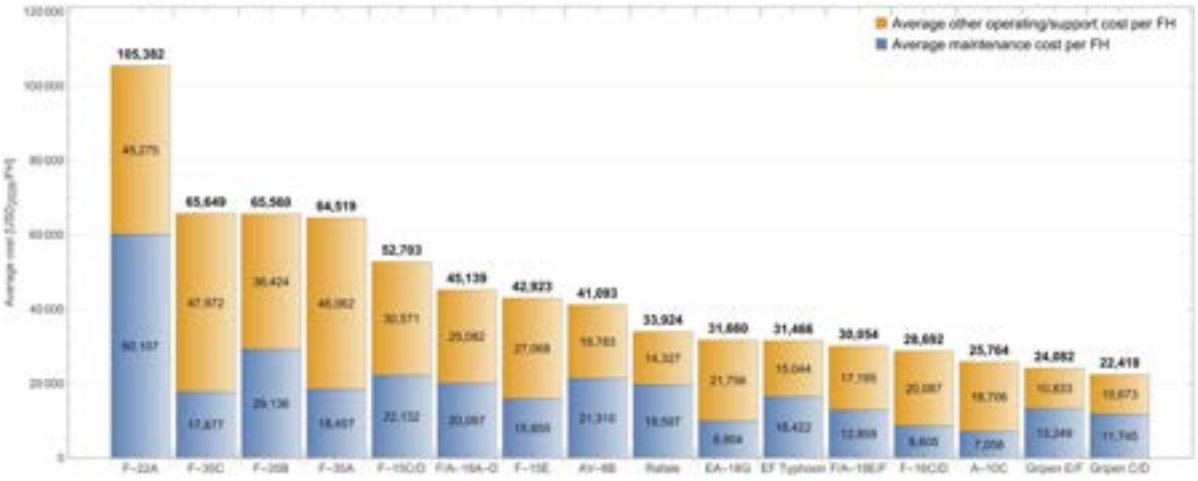


Figure 1. *Fighter aircraft operating costs reported in [b] and [c] in constant fiscal year 2026 USD.*

The dimensionality reduction was done using the Singular Value Decomposition (SVD) analysis described in . It takes the intrinsic correlations between aircraft design parameters and transforms these into a smaller set of synthetic orthogonal parameters ordered by importance. This allows complex relationships to be approximated by only a few parameters, yielding much better results than simple correlation analysis. For the matrix-shaped dataset X, there exists a decomposition of the form:

$$X = s \times w \times V^T$$

Where s is an orthogonal input vector, w is a diagonal matrix with the singular values ordered by importance which weights how dominant design variables are. V is an orthogonal matrix that rotates the coordinate system from the original axes into the new axes.

3. Results / Conclusions

The most important design parameters regarding dominance on the results are the number of engines ($nEng$, w-diagonal = 1.31), wing loading (W/S, w-diagonal = 0.94), and thrust loading (T/W, w-diagonal = 0.76), with all of the other's parameters importance decreasing almost linearly. After performing the SVD analysis and setting all other s factors to zero, the solved Cost Per Flying Hour (CPFH) equation is:

$$CPFH = 3.1607 \times 10^{-8} \frac{(T/W)^{0.608315}\ (W/S)^{4.56543}}{nEng^{1.42082}}\ [USD_{2026}/FH]$$

An example application to a fighter aircraft concept that was not built is the Rockwell D703-2 , which would have weighted 16,871 [kg] with 27.13 [m²] of wing area and two General Electric F404J engines producing 48.9 [kN] of dry thrust each. The estimation for the model yields a CPFH of 48,623 [USD/FH], which would lie in-between the F/A-18 and the F-15C/D.

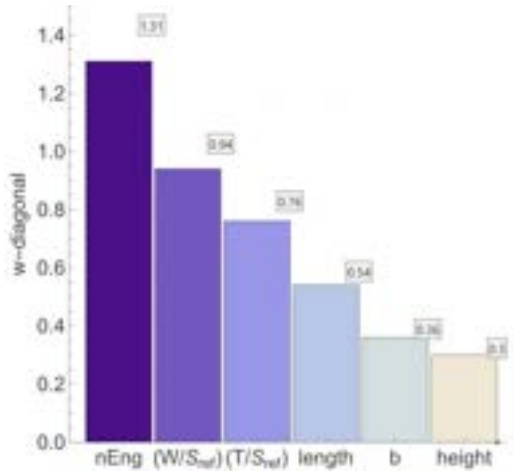


Figure 2. *Weights of design parameters*

Applying the SVD analysis allows for a mapping between design parameters and expected operating cost per flying hour. For the case of the aircraft considered, the most important parameters determining the cost are also the main design variables used during initial design. The resulting level-0 model is therefore quite useful for an initial design space exploration, as long as its limitations are considered and respected. The goal is not to provide a comprehensive prediction of the cost per flight hour of operating a fighter, but rather a semi-empirical computationally cheap method that aids during concept evaluation.

A data model centered MDO discipline integration in GEMSEO applied to industrial conceptual aircraft design

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1. Introduction and Objectives

Although industrial MDO frameworks are mature, preparing MDO studies often requires more human effort than executing them. A major bottleneck lies in integrating different disciplines with the framework, particularly when several disciplines, a large number of input/output variables, or multiple execution modes are involved. Most MDO frameworks such as

OpenMDAO [Grey 2019] and GEMSEO [Gallard 2018] rely on internal data models that store information as mappings between string-based data names and values. Consequently, simulation interfaces must declare active inputs and outputs during initialization and then access and update them consistently through string manipulation during execution. Ensuring consistency between declared and manipulated variables usually necessitates extensive manual verification, rendering these configurations susceptible to errors. This issue becomes increasingly critical as the number of disciplines and data exchanges grows, thereby limiting the industrial scalability and robustness of MDO methodologies.

2. Methodology

The proposed approach is based on a new paradigm for integrating disciplines via the automatic discovery of input and output data names, combined with an object-oriented description of MDO data. Using a central data model is not a new idea: the CPACS data model, based on XML, dates from 2012; more recently, there is the Aircraft Data Hierarchy [Engelbeck, 2026], on which the Standard Evaluator model integration approach is based [Gablonsky, 2026]. These paradigms allow bridges to be built with other engineering areas, such as system engineering and graphical representations of products, as well as the generation of numerical models [Klimmek, 2019]

The innovative aspect of the methodology lies in combining a central data model with the introspection capabilities of the Python programming language, such as runtime attachment of decorators to objects and analysis of the code using the Abstract Syntax Tree.

We demonstrate the benefits in terms of the integration of complex industrial workflows in a conceptual MDO design process involving more than 50 disciplines from Bombardier Inc.

We compare the complexity metrics of the code (Cyclomatic complexity, maintainability index and number of lines) for representative disciplines in the standard integration approach and the proposed paradigm. These quantitative metrics are known to be indicative of development time and maintenance costs, which are one of the current bottlenecks in industrial MDO.

3. Results / Conclusions

The Figure 1 visually illustrates the benefits of the approach on the source code of the Discipline integration. The data model is



Figure 1. *Toy problem comparison of the standard discipline integration in GEMSEO (left), with the proposed approach (right) shows a division by two of the number of lines of code in the Discipline as well as a removal of the error-prone magic strings.*

Metrics	Standard Discipline	Discipline from Model	Gain
Number of lines	1528	1067	30%
Cyclomatic Complexity	283	103	63%

Table 1. *Comparison of the standard discipline integration in GEMSEO (left), with the proposed approach (center) associated with a data model based on Pydantic (right) shows a division by two of the number of lines of code in the Discipline as well as a removal of the error-prone magic strings.*

Hybrid physics-based and operations-aware ML surrogate for spacecraft life support systems

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1. Introduction / Objectives

Current Life Support System (LSS) operations for crewed missions rely heavily on ground-based monitoring and control. While a model-based approach to simulating the LSS is possible, the high-fidelity required leads to long runtimes and increased computational load. This approach becomes impractical given more dynamic and variable activities, such as more frequent extra-vehicular activities or shorter crew-rotation periods.
The presented work features a hybrid approach to simulating and predicting LSS behavior. A low-fidelity, low-cost simulation is used for long-term behavior and a machine learning (ML) model, employing an operations-aware architecture, enhances fidelity in short-term horizons and adapts to the current operational state.

2. Methodology

The Virtual Habitat (V-HAB) framework provides a dynamic and flexible tool to simulate various LSSs. A complex lunar-gateway station was modelled in V-HAB, encompassing all major subsystems. A crew of three astronauts was simulated with varying metabolic loads using the DetailedHuman model in V-HAB, including activities such as physical exercise or sleep. The simulation entails multiple modules and different operational states, extending to extra-vehicular activities, crew rotation or unmanned operation.
The physics-based model was then simplified with regards to computational time and system complexity. An analytical model of the condensing heat exchanger was derived and

redundancy of individual systems was eliminated. The detailed astronaut model was replaced with a simplified version to further reduce computational requirements.

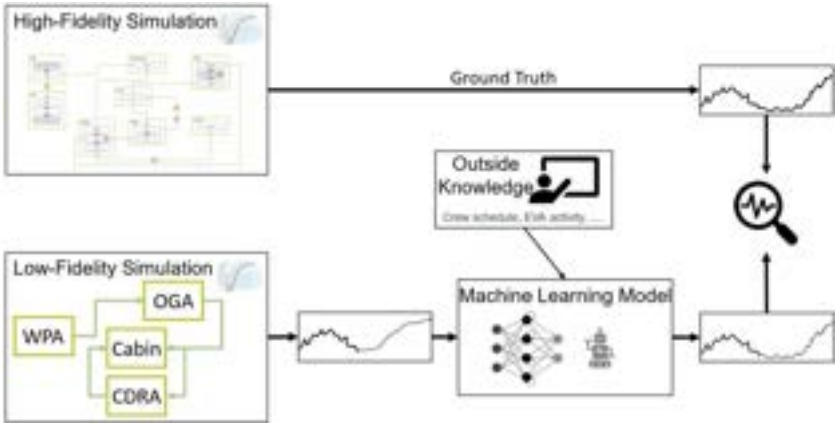


Figure 1. *Simplified block diagram of the overall architecture developed for the study. The high-fidelity simulation purely serves as the ground truth and only a low-fidelity simulation and outside knowledge is provided to the machine learning model.*

A data set consisting of various crew schedules was generated for both models, with the high-fidelity simulation serving as the reference ground truth for evaluation.
After ML model training, a prediction is obtained by combining the low-fidelity simulation results with operational information such as the current crew schedule and feeding the composite input to the ML model. This architecture is visualized in Figure 1. Additionally, a pure ML-based approach was tested by substituting the low-fidelity simulation entirely with a more generalized ML model.

3. Results / Conclusions

The study highlights the importance of ML in human spaceflight. The hybrid approach described herein enables operations-aware autonomy and serves as a foundational step toward a predictive control strategy for future missions. Employing a ML model enabled faster predictions of the current LSS behavior and operational state with high fidelity, yielding a considerable improvement in accuracy while reducing computational time compared with earlier digital twin applications in which the entire LSS was simulated in detail. The method can be integrated alongside routine ground control operations, provided that external knowledge, such as the current crew schedule, is supplied. However, the ML approach demands extensive work on simulations, making it challenging to adopt during early project phases. Future work will therefore focus on developing a more generally applicable ML model.

MDAO formulations based on disciplinary surrogate models

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1. Introduction

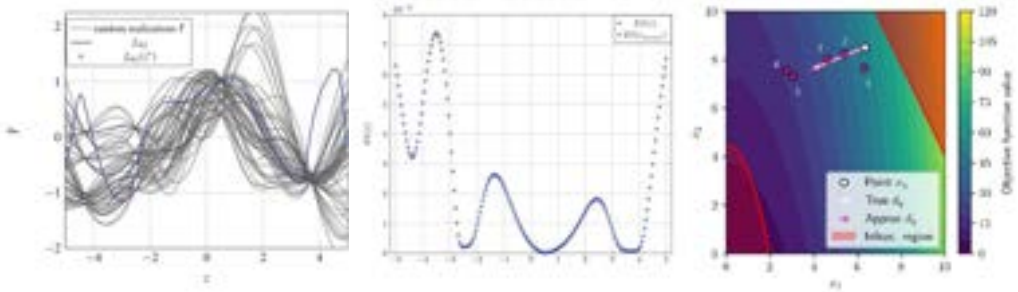
For decades, surrogate based optimization (SBO) has been a research topic in non-linear optimization. Many results have proven the efficiency of this approach for both global optimization (e.g. Bayesian Optimization (BO)) and local optimization (e.g. surrogate-based trust region). An extension to multidisciplinary design analysis and optimization (MDAO) seems natural, and several studies have proposed adapting SBO to this context. However, despite its apparent simplicity, this extension presents unique challenges. This work focuses on using disciplinary surrogate models, as opposed to considering the full multidisciplinary analysis (MDA) as a single black-box function. Approximating only the costly disciplinary solvers of the MDA by disciplinary surrogate models offers several advantages, including a more flexible framework that allows for easy coupling of high-fidelity sources of information and a better management of the computational resources.
Our initial attempt in this area involved using Gaussian process surrogate models, similar to those in traditional BO algorithms, to balance the exploration of the design space and the exploitation of the surrogate models. This approach was implemented in an algorithm called Efficient Global Multidisciplinary Design Optimization (EGMDO) and its constrained extension, C-EGMDO . Compared to classical BO, a first difficulty arises from the nonlinear coupling between the different GP surrogate models, which leads to a non-Gaussian model of the objective function. A second difficulty arises from the dimension of the coupling variables. In high-dimensional cases, such as the coupling between PDE solvers, reduced-order modeling is proposed in conjunction with GP surrogate models.
Besides its appealing global convergence capability, BO may struggle to converge toward a minimum in some cases where a gradient-based approach would be much more efficient. For this reason, proposed using the same disciplinary GP surrogate model strategy with gradient based optimization. This results in a different adaptive sampling strategy designed to approximate the gradient of the function rather than its value.

2. Methodology

The first step of the proposed method is to build initial disciplinary surrogate models of the disciplinary solvers involved in the multidisciplinary analysis. One difficulty is properly sampling the coupling variable space for each disciplinary solver. This issue is addressed in through an iterative sampling scheme between the coupled disciplinary solvers.

The second step involves solving what we call the random MDA for different design points, which form an initial Design of Experiments (DoE). In its simplest form, this step solves the MDA for different random realizations of the disciplinary GP, which leads to Monte Carlo estimators of the random distributions of the MDA solution, the objective and the constraint functions. The third step uses these probability distributions to determine which point(s) should be added to the DoE to improve one or more of the disciplinary GP surrogate model(s). This study focuses on this task and proposes comparing three strategies.

- Global enrichment: BO using the C-EGMDO formulation proposed in (see Figure 1 a)
- Local enrichment: Gradient approximation based on the local enrichment procedure proposed in (see Figure 1 b)
- Hybrid enrichment: combining global and local search through a trust-region framework inspired by .



a b

Figure1 : *a) Global search : Illustration of the random realization of the objective function on a 1D example and corresponding EI (from) b)Local enrichment to improve gradient accuracy: Illustration of the gradient approximation after 5 enrichments on a 2D example (from)*

3. Conclusions

Building disciplinary surrogate models is an appealing option for managing the complexity of the MDAO problem. However, monitoring the accuracy of these surrogate models is crucial. Several examples in and demonstrate that, as with monodisciplinary optimization, adaptive construction of disciplinary surrogate models outperforms a priori construction in terms of accuracy and numerical cost. The present study will compare three different adaptive construction schemes on an aircraft wing aeroelastic test case. This test case involves high-dimensional coupling variables and can be parameterized by different sets of design variables to vary the degree of complexity. In addition to quantitative comparisons in terms of convergence and number of disciplinary solver evaluations, the goal is also to provide guidelines for using disciplinary surrogate models in MDAO formulations.

Acceleration of the Bi-Level BCD MDO Architecture Applied to Aircraft Design

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1. Introduction / Objectives

Multidisciplinary Design Optimization (MDO) is emerging as a key methodology for the systematic design of aircraft, taking into account the interactions between multiple disciplines. Although monolithic MDO architectures are computationally efficient, they are often ill-suited for industrial applications where design disciplines are handled by different departments and gradient information is unavailable. Distributed MDO architectures, such as the Bi-Level Block Coordinate Descent (Bi-Level BCD) framework proposed by David et al. , effectively address these organizational shortcomings. However, their computational cost remains significantly higher than that of monolithic alternatives. To resolve this limitation, we

propose accelerations to the Bi-Level BCD architecture by introducing bounded fixed-point acceleration techniques to both the BCD and multidisciplinary analysis (MDA) solvers. The resulting computational gains are demonstrated through an aircraft design case study using mid-fidelity analysis tools, orchestrated via the GEMSEO framework.

2. Methodology

As shown in Figure 1, the Bi-Level BCD architecture consists of a BCD solver and two MDA solvers. The BCD solver ensures the convergence of design variables between disciplinary optimizations, while the MDAs resolve disciplinary couplings. Concurrently, the system-level optimizer drives tradeoffs between the disciplinary optimizations using system-level design variables to minimize a global objective. Because the MDA and BCD solvers address fixed-point problems, their convergence can be accelerated using algorithms such as Anderson acceleration. However, for the BCD solver, which minimizes the residual of disciplinary design variable updates, a bound or constraint must be enforced on the acceleration step to respect design variable limits. We implement this bounded acceleration methodology within the GEMSEO framework to enable faster BCD and MDA iterations, ultimately reducing total optimization time.

In this work, this methodology is applied to a NASTRAN aeroelastic model of the high aspect ratio undeflected Common Research Model (u-CRM 13.5) , involving wingbox FEM sizing and aerodynamic shape optimization. Additionally, aileron sizing is integrated to evaluate the tradeoff between handling qualities and load alleviation. The resulting Bi-Level BCD MDO problem is formulated and solved within the GEMSEO optimization framework.

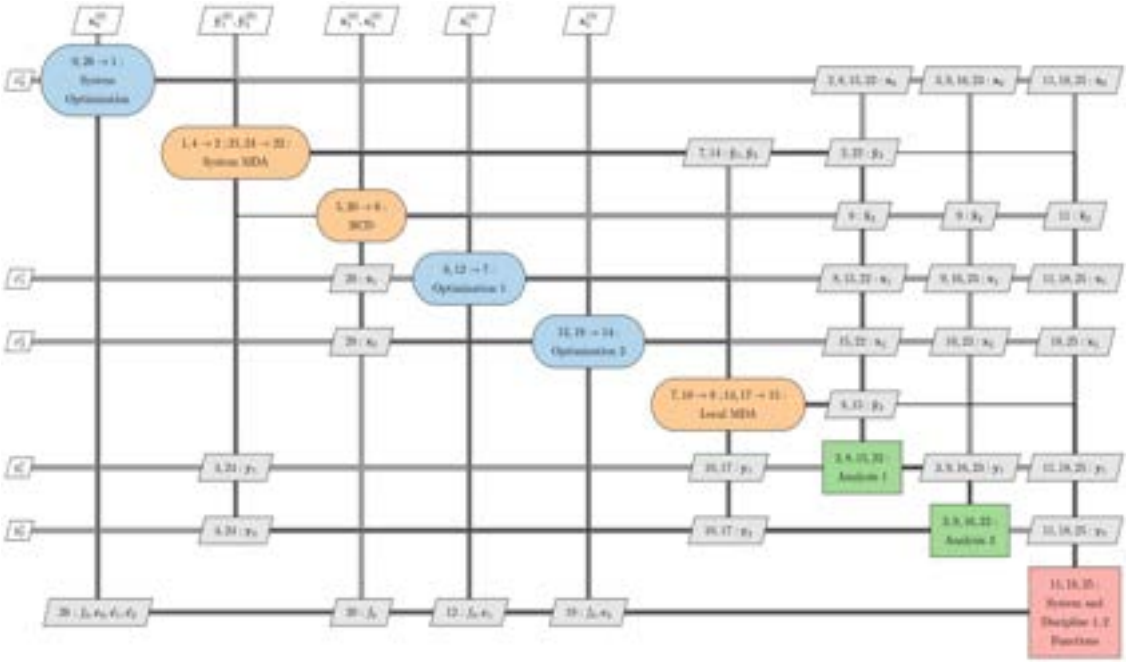


Figure 1. *XDSM of the Bi-Level BCD-MDF architecture (based on David et al. , with modifications)*

3. Results / Conclusions

Initial tests of the accelerated Bi-Level BCD architecture on the Sobieski SSBJ benchmark demonstrate a significant reduction in disciplinary function calls. Furthermore, the proposed aeroelastic MDO application using the high aspect ratio u-CRM benchmark will provide deeper insight into the convergence characteristics and acceleration capabilities of the Bi-Level BCD architecture for practical, industrial-scale MDO problems.

Topology optimization of composite structures using curved Double-Double laminates

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1. Introduction / Objectives

Recently, the simultaneous optimization of structural topology and fiber orientation has attracted substantial research interest . Density-based and evolutionary methods treat the local fiber angle as an additional design variable, and level-set-based approaches have been applied to composite structures with curvilinear fiber paths. Our framework further integrates topology and fiber content optimization with additive manufacturing constraints, enabling complex variable-stiffness structures via material extrusion 3D printing, as shown in Figure 1. Among the strategies investigated, the offset-type fiber layout yielded the highest stiffness compared with constant layouts . Building on this result, the present work introduces a curved Double-Double (DD) laminate, in which the offset-type primary orientation varies in space and the secondary orientations are derived through a square-symmetric scheme. The objective is to further increase the stiffness of the optimized structure while preserving manufacturability, and to validate the framework through topology optimization, continuous-fiber 3D printing, simulation, and experimental testing.

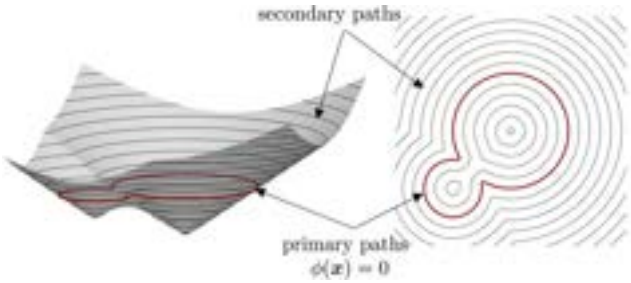


Figure 1. *Level set method for the continuous fiber-based topology optimization.*

2. Methodology

The proposed methodology integrates the DD laminate concept into a level-set-based topology optimization framework for fiber-reinforced composite structures, and validates the resulting design through additive manufacturing and experimental testing. The complete procedure consists of four stages: design, manufacturing, simulation, and validation. In the design stage, a level-set function defines the structural domain, while its gradient is used to

compute the primary fiber orientation ϕ at every material point, producing offset-type curvilinear fiber paths that follow the level-set isocontours of the design domain. The conventional DD laminate of $[\phi/-\psi/-\phi/\psi]$r is then extended to a curved DD laminate, in which the primary orientation ϕ varies in space and the secondary orientation is generated using a square-symmetric scheme ($\psi = 90° - \phi$). The remaining orientations are derived accordingly. The homogenized stiffness of the curved DD laminate is then evaluated and supplied to the topology optimization loop, which iteratively updates the level-set function to minimize structural compliance under a prescribed volume constraint. Figure 2 shows an overall flowchart of the DD laminate-based topology optimization.
To enable additive manufacturing, an in-house converter based on a wave-function representation transforms the discrete fiber orientation field into continuous, printable fiber paths. The resulting paths are translated into G-code for an Anisoprint continuous-fiber 3D printer, which co-deposits a thermoplastic matrix and continuous carbon fiber reinforcement. Finally, a bending deformation test combined with Digital Image Correlation (DIC) is performed to compare strains and load–displacement responses against the simulation, and to benchmark the curved DD laminate against single-orientation laminate baselines.

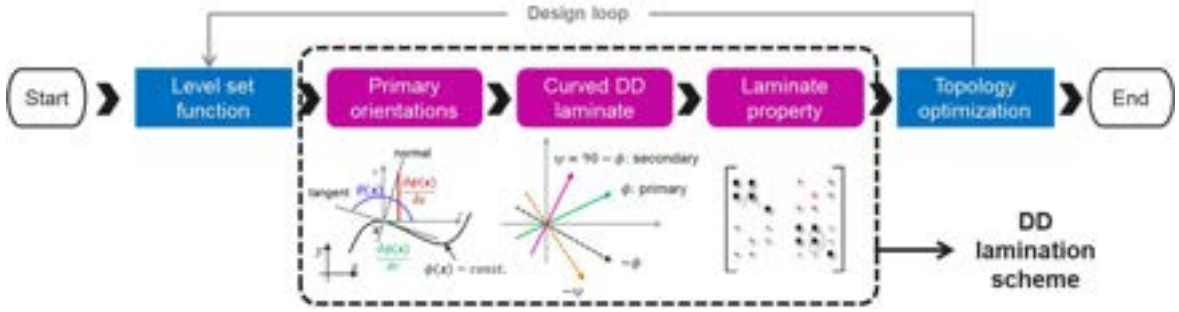


Figure 2. *Overall flowchart of the DD laminate-based topology optimization.*

3. Results / Conclusions

The proposed framework was demonstrated on a benchmark MBB-type beam, where a 50% mass-reduction target was achieved with converged compliance and volume histories. Three fiber-layout strategies built on the same optimal topology were compared: (#1) the curved DD laminate of $[\phi/-\psi/-\phi/\psi]_4$, (#2) a single primary laminate of $[\phi]_{16}$, and (#3) a single-secondary laminate of $[\psi]_{16}$. Specimens were 3D-printed with continuous carbon fiber and tested in a custom bending jig with DIC measurements. Numerical and experimental load–displacement responses, as well as point-wise strains, showed good agreement, validating the design and simulation chain. The curved DD laminate exhibited the highest stiffness, outperforming the single primary and single-secondary laminates by 20.2% and 40.5%, respectively. These results confirm that the curved DD laminate concept provides an effective and manufacturable route to enhance composite structural performance through anisotropic topology optimization.

High-Order Beam Modelling of Tapered Composite Wing Structures

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1.Introduction / Objectives

Modern aircraft wings are characterized by pronounced variations in geometry, stiffness and advanced material layout along the span, resulting in tapered and non-prismatic composite wing-box structures. Such configurations exhibit complex structural phenomena, including warping, transverse shear effects and bending–torsion coupling , which are difficult to capture using conventional one-dimensional beam theories based on constant cross-sections . Although detailed shell and solid finite-element models provide high accuracy, their computational cost becomes prohibitive for preliminary design, aeroelastic analyses and multidisciplinary optimization studies .

This work introduces a high-order non-prismatic FE beam based on the Carrera Unified Formulation (CUF) for the efficient modelling of tapered composite wing structures . The suggested approach scientific novelty lies in enhancing the refined CUF beam models to simulate composite structures showing cross-sectional variations throughout the interpolation of sectional geometry, material properties and laminate distributions along the beam axis. The objective is to retain the accuracy of high-fidelity three-dimensional models while reducing the computational time by a unified one-dimensional framework suitable for realistic aerospace applications.

2.Methodology

The suggested methodology is based on high-order CUF beam elements , where the three-dimensional displacement field is approximated over the cross-section through hierarchical Taylor or Lagrange expansions. This refined kinematic description enables accurate representation of transverse mechanical responses.

In the case of tapered composite structures, representative cross-sectional stations are introduced along the beam axis to capture the variation of geometry, stacking sequence and material properties over the span . The sectional quantities are interpolated between adjacent stations, allowing the beam element to represent non-prismatic configurations with continuously varying stiffness and mass distributions.

The formulation is implemented in an in-house finite-element framework and assessed through benchmark analyses involving composite wing-box structures. The validation campaign includes tapered configurations, such as cantilever composite beams with linearly varying dimensions and representative wing-boxes featuring (skins, spars or rib). Numerical predictions of non-prismatic beams are compared against high-fidelity shell and solid finite-element solutions.

Structural responses are evaluated in terms of displacement fields, stress and strain distributions and bending–torsion coupling. In addition, the influence of the mesh size and interpolation order is investigated to identify the trade-off between numerical accuracy and computational efficiency. The computational performance of the suggested approach is assessed through degrees of freedom and CPU time comparisons against detailed GFEM and three-dimensional finite-element models.

3. Results / Conclusions

The developed methodology is expected to enable accurate prediction of tapered composite structures mechanical responses within a refined one-dimensional high-order framework. By extending CUF beam models to non-prismatic configurations with spanwise-varying geometry and material properties, the formulation aims at capturing transverse responses typically outside the limits of classical beam theories.
The interpolation of sectional properties along the span is expected to provide an efficient representation of stiffness gradients and tapering effects while maintaining a significantly reduced computational cost compared with detailed shell and solid finite-element models. The approach is therefore intended to combine the accuracy of high-fidelity structural analyses with the efficiency required for preliminary aerospace design and optimisation studies.
The framework is envisioned as a computationally efficient tool for the analysis of realistic tapered composite wing airframes and could potentially be employed in iterative optimisation and multidisciplinary design environments, where fast yet accurate structural evaluations are essential for the design and sizing of more realistic aerospace configurations.

A Multi-Objective Optimization Framework for Sustainable and Strategic Airframe Material Composition in Conceptual Aircraft Design

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1. Introduction / Objectives

Multidisciplinary Design Optimization (MDO) is widely used for preliminary aircraft design, balancing aerodynamic and structural performance to minimize fuel burn. However, current MDO often considers a single material on the structure of the aircraft, leaving the effect of material composition on the overall aircraft design (OAD) unexplored. This omission is critical, as the industry faces severe supply chain volatility for Critical Raw Materials (CRM) and increasing pressure to reduce life-cycle environmental impact. Modern composite-heavy airframes present challenges regarding non-recyclable End-of-Life (EOL) and reliance on materials like Titanium. This study introduces a novel Multi-Objective Optimization (MOO) methodology to address this gap. The main objective is to integrate aero-structural performance objectives with environmental factors (manufacturing, EOL) and material criticality constraints to define an optimal and future-proof material composition at the conceptual design stage.

2. Methodology

The proposed methodology implements a multi-objective optimization (MOO) approach integrated within the Overall Aircraft Design (OAD) framework. The open-source tool Transport Aircraft System OPTimization (TASOPT)[1] is used as the baseline for the aircraft sizing

and performance loop. This study expands upon the existing MOO framework by performing material selection as a continuous optimization problem[2]. The optimization is formulated with the following objectives and constraints:

- Objectives: Minimize overall aircraft weight, block fuel consumption (for operational impact), manufacturing environmental impact (e.g., CO2 intensity and energy), and non-recyclable waste (End-of-Life impact).
- Design Variables: Material composition mix fraction (Aluminium, Carbon Fiber Reinforced Polymers (CFRP), Titanium, and Steel).
- Constraints: Minimum material fraction requirements, Material Criticality, and Material interdependencies (e.g., increased use of Titanium fasteners with CFRP).

The approach employs a surrogate modeling technique to link the material composition and constraint parameters to the overall aircraft design outputs (Empty Weight, Fuel Burn).

3. Results / Conclusions

The presented framework enables comprehensive trade-off studies that capture the complex, systemic relationships between technical performance requirements (block fuel) and strategic sustainability constraints. By integrating material selection as an optimization problem within the Overall Aircraft Design (OAD) loop, the methodology provides aircraft designers with actionable insights for informed material selection decisions during the conceptual stage. This approach specifically allows for the evaluation of how varying compositions of Aluminium, Carbon Fiber Reinforced Polymers (CFRP), Titanium, and Steel influence critical outputs such as aircraft empty weight and fuel burn.

Machine-Learning-Assisted Transfer Matrix Analysis of Cutout-Induced Imperfections in Rotationally Symmetric Shell Structures

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1. Introduction / Objectives

Rotationally symmetric shell structures are widely used in aerospace applications due to their efficient load-carrying behaviour. For such structures, Transfer Matrix Methods provide an efficient semi-analytical alternative to finite element analyses, particularly when repeated evaluations are required in preliminary design . In practice, however, ideal rotational symmetry is often disturbed by local features such as access openings, inspection holes, or other cutouts. These discontinuities cause non-axisymmetric stress redistributions that cannot be represented by purely axisymmetric shell formulations. Previous studies have considered initial geometric deviations in transfer-matrix-based shell analysis , but local cutout-induced discontinuities have not yet been systematically addressed. The objective of this study is to investigate how such local disturbances can be incorporated into a Transfer Matrix Method framework by replacing the cutout region with a data-driven propagation model. This enables efficient approximation of local stress effects while extending the method beyond ideal shell structures.

2. Methodology

The proposed methodology combines a semi-analytical Transfer Matrix Method with a data-driven surrogate model for local cutout regions. In the Transfer Matrix Method, the shell equations of an ideal rotationally symmetric structure are formulated along the meridional coordinate, while the circumferential dependence of displacements and stress resultants is represented by Fourier components. This leads to an efficient one-dimensional propagation of the mechanical state through undisturbed shell segments. A representative rotationally symmetric shell structure with a localized cutout is divided into ideal shell segments and a disturbed segment containing the discontinuity. The ideal segments are treated with the classical Transfer Matrix Method. The segment containing the cutout is not described directly by the Transfer Matrix Method. Instead, it is replaced by a machine-learning-based propagation operator that estimates the relation between the Fourier-based mechanical state before and after the disturbed region. The state vector at both segment boundaries contains the relevant displacement and stress-resultant quantities expressed by a finite set of circumferential Fourier coefficients. Since the cutout breaks the rotational symmetry, the surrogate model accounts for the resulting interaction between different Fourier components and predicts the redistributed mechanical state behind the cutout. Training data for the surrogate model are generated from finite element simulations in which the cutout geometry is explicitly resolved. A set of representative shell configurations, cutout dimensions, positions, and loading states is analysed to obtain input-output pairs for the local state propagation. From these simulations, the boundary states before and after the cutout segment are extracted and transformed into the Fourier representation used by the Transfer Matrix framework. The complete hybrid model is evaluated by propagating the structural state through undisturbed shell regions using the Transfer Matrix Method and through the cutout region using the trained surrogate model. Independent finite element reference simulations are used for validation. The comparison focuses on the predicted Fourier coefficients, displacement response, stress resultants, and local stress redistribution caused by the cutout. In addition, the influence of the number of retained Fourier components and the accuracy of the surrogate-based propagation are investigated.

3. Results / Conclusions

The results demonstrate that the proposed hybrid TMM-ML methodology provides an efficient approach for modelling cutout-induced imperfections in rotationally symmetric shell structures. By replacing only the disturbed cutout region with a data-driven propagation operator, the method captures the associated coupling between circumferential Fourier modes while preserving the efficiency of the Transfer Matrix Method in the remaining ideal shell segments. Comparisons with finite element reference simulations show that the predicted modal states, displacement response, and stress resultants remain within acceptable error margins for the investigated configurations. The approach therefore enables fast evaluation of local cutout effects without requiring a full finite element analysis for each design variation. This makes the method particularly suitable for repeated analyses, parametric studies, and early-stage design workflows where scalable reduced-order models are required for multidisciplinary design optimization.

Liquid Hydrogen Technologies for Sustainable and Climate-Neutral Aviation (H2ELIOS Project)

Chaired by:
Ms. Emma Celeste Lope Retuerto (Sonaca, Spain)

LH_2 Tank Demonstrator Design, Manufacturing and Assembly

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Aciturri, Spain

The development of liquid hydrogen (LH_2) storage systems is a key enabler for future zero-emission aviation. Among the main technological challenges, the integration of lightweight structures, efficient thermal insulation and safe operation under cryogenic conditions require a holistic design approach. Within the Clean Aviation project H2ELIOS, a full-scale LH_2 tank demonstrator has been developed to validate these aspects.
The tank architecture** is based on a non-integral dual-tank configuration, composed of a inner tank (IT) containing the liquid hydrogen and a composite outer tank (OT) providing structural resistance and external sealing. A multi-layer insulation system, has been implemented to minimize heat ingress while maintaining integration feasibility. The objective is to enable the storage of 150 kg of liquid hydrogen within a timeframe compatible with aeronautical requirements, while maintaining a very high gravimetric index thanks to the use of composite materials to reduce weight.
The design has been supported by a manufacturing strategy integrating conventional processes and advanced composite fabrication techniques. Particular attention has been paid to sealing concepts, tolerance management and accommodation of thermal contractions through dedicated IT–OT support systems. The assembly process follows a phased approach, including internal systems integration, insulation installation, IT–OT alignment and final instrumentation. This enables accurate positioning and repeatability, which are critical for subsequent testing.
The demonstrator will undergo a dedicated LH_2 test campaign to assess structural integrity, thermal performance and system operability under representative conditions. The results are expected to provide key insights into cryogenic tank behavior, as well as to support validation of design assumptions and future certification activities.

** The H2ELIOS cryogenic tank concept for storing liquid hydrogen is patent protected under a patent owned by Aciturri.

Acknowledgement: The project H2ELIOS is supported by the Clean Aviation Joint Undertaking and its members. Funded by the European Union. However, views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

Experimental validation of a LH2 tank Thermo-fluidic Digital Twin

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1. Introduction / Objectives

Global decarbonization efforts have placed the aviation sector at a critical turning point. Under the framework of the Clean Aviation Joint Undertaking, transitioning to hydrogen-powered aircraft has emerged as a primary strategic pillar. However, the adoption of Liquid Hydrogen (LH2) introduces significant integration challenges. As a cryogenic fluid, LH2 demands specialized storage and handling systems that must reconcile extreme thermal requirements with stringent aircraft constraints regarding weight, operational functionality, and safety. Modeling of the tank storage designs is of paramount relevance in order to facilitate the design process but there is a strong need of experimental results to validate the models and their assumptions.

2. Methodology

The present paper leverages the fact that the H2ELIOS project is currently under its experimental phase, then for the first time there is the opportunity to compare the measured values with the numerical results of the developed LH2 Tank Digital Twin . The tank specimen has been sensorized with multiple thermocouples and other sensors to follow up the temperature, pressure and mass flows for different scenarios, then providing an excellent opportunity for validation.

3. Results / Conclusions

Functional tests will cover different scenarios involving Nitrogen and Hydrogen. The objective of the paper will be to leverage those tests to validate three main pillars of the Digital Twin predictions: i) the insulation performance of the suggested double-foam architecture; ii) the transient response of this envelope; iii) the fluidic response in gas-only situations as gas cooldown process, and others with cryogenic liquid, like dormancy and boil-off.

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An Attempt at Validation of Means of Compliance (MoC) for the Permeability of LH2 Tank Wall Materials

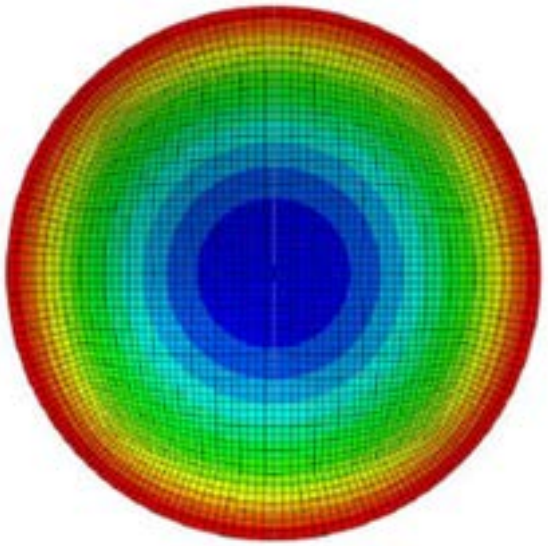
A. B. Horvat, G. Dreossi
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The European Union Aviation Safety Agency (EASA) is, together with industry stakeholders via various platforms and projects, deeply invested in the development of a new set of rules and

regulations, required for the eventual certification of zero-emission aircraft and their associated subsystems. The liquid hydrogen (LH2) storage solution is one of the most safety-critical subsystems, both from the design and integration perspective, and will surely be instrumental in H2 aircraft certification (1). That's why H2ELIOS, a Clean Aviation project dedicated to the development of an innovative LH2 tank for aviation (Figure 1), dedicated a sub work package to the generation of an MoC, that addresses tank wall permeability/leakage and will eventually aid manufacturers in the wall material selection process. The authors' initial and revised approach to this work was presented at TSAS 2025, whereas this paper outlines the MoC validation test plan results.

Figure 1. *The H2ELIOS LH2 storage system concept**

It being the scope of the proposed MoC was limited to polymer-based, composite LH2 tank walls, two different CFRP material systems were evaluated in the validation test campaign. Measuring and monitoring the movement of steady state leak rate, prior and subsequent to sample conditioning, sat at the core of the campaign, so as to determine if the leak rate is acceptable/manageable or a "moving target". Two different conditioning methods were employed: 20 cycles of thermal loading from 323 K to 77 K, followed by 50 rounds of multi-axial mechanical loading at 77 K. All permeability testing was performed both at room temperature and 77 K, using a Pfeiffer ASM-340 leak detector and helium as a tracer gas. The Abaqus finite element analysis tool was used to better understand sample behaviour and target desired conditioning strains (Figure 2), while strain itself was measured using optical fiber Bragg grating sensors.



Three complete rounds of conditioning were performed on each material system, followed by permeability testing. Results, in both cases, show that the conditioning had a negligible effect on steady state leak rate, when compared to that of pristine samples. Though this is good, because it indicates a predictable steady state leak rate that tank manufactures can work with and design around, the authors believe it puts the chosen mechanical loading method into question. The results of subsequent permeability tests, performed with the samples in the bulged or flat configuration, show higher values for the former, thus indicating the importance of measuring permeability of samples in the strained state, in order to attain application-relevant results. This study highlights the importance of testing samples in relevant conditions and corroborating the results with sufficient modelling data, in order simulate the aforementioned conditions as best as possible. The authors hope and trust their findings will be used to better future MoC test campaigns and hence contribute to future zero-emission aircraft rules and regulations.

Figure 2. *Depiction of the strain field generated in the first ply of a composite circular disc,*

being subjected to a bulge test at 77K.

The Representativeness of Helium for LH_2 Tank Permeability Testing: A Comparative Study

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There are a number of practical and analytical reasons why using helium (He), instead of hydrogen (H_2), as a permeability test tracer gas, is preferable. It's safer, more instrument-friendly (i.e. sensitivity) and typically yields similar and/or slightly higher permeability when compared to H_2, thus making it a conservative choice of tracer gas. This is covered well in literature and nicely summarized in (1). Given, however, the crucial role LH_2 tanks and their inherent permeation/leakage will play in the certification of future zero-emission aircraft (2), fully understanding this relationship between He and H_2 permeability, particularly in cryogenic conditions and particularly its dependence on the material system chosen, is of utmost importance. Permeability experiments were performed to address this topic within the scope of Means of Compliance (MoC) validation testing in Clean Aviation project H2ELIOS*, a project dedicated to the development of an innovative LH2 tank for aviation, the results of which are presented in this study.
Tests were performed on two different CFRP material systems, using pure 100% He gas, 5%He/95%N_2 forming gas and 5%H_2/95%N_2 forming, so as to ensure safety. They were performed using a Pfeiffer ASM-340 leak detector in conjunction with an in-house built test apparatus, which allows for 3 samples to be tested at the same time and thus significantly speeds up the test campaign. Tests were conducted both at 323 K and 77 K. Initial results already show steady state leak rates at 77K that are multiple decades lower than the ones at 323 K, while other differences in recorded leak rate still need to be evaluated in order to understand their origin. The investigation of this study's results will provide significant insight into the understanding of the relationship between helium and hydrogen permeability on dedicated LH2 tank materials, specifically addressing their representativeness. Additionally, it will provide future test campaigns with recommendations on how to address the higher H_2 testing instrument background and minimize its effect on result reliability.

Assessment of Structural and Leakage Behavior of Gasketed Bolted Flange Joints for Cryogenic Applications

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1. Introduction / Objectives

Bolted flange joints are commonly used in applications regarding the containment and transfer of fluids. Storage and transfer of cryogenic fluids is common in aerospace applications, such as the Liquid Hydrogen (LH_2) tank developed within the framework of the Clean Aviation Joint Undertaking project H2ELIOS . In addition, bolted flange joints are used in applications involving Liquid Oxygen (LOx), Liquified Natural Gas (LNG) and Liquid Ammonia (LNH_3), which are among the most common rocket propellants. Due to the strict weight requirements of aerospace structures, weight should be minimized without compromising safety. Significant attention should therefore be given to stresses and potential leakage while accounting for multiple loading conditions. The severe thermal loads introduced by cryogenic conditions render sizing and assessment calculations complicated and time consuming. In this direction, the present work refers to the development and validation of a parametric high-fidelity thermomechanical finite element modelling methodology for bolted flange joints with gaskets for cryogenic applications.

2. Methodology

The developed methodology is based on parametric high-fidelity finite element modelling using ANSYS APDL environment. The flange assembly includes the flange, bolts, nuts and gasket, while cyclic symmetry conditions are employed to reduce computational cost by modelling only a representative section containing a single bolt. The model incorporates temperature-dependent material properties, contact interfaces with friction, bolt pre-tension and coupled thermomechanical loading conditions representative of cryogenic applications.

Pressure loading is applied through a combined approach consisting of internal pressure on the inner surfaces and distributed tensile forces on the flange rim in order to accurately reproduce pressure induced separation forces. Additionally, a dedicated liquid pressure application methodology is implemented for gasket separation regions, where pressure is progressively applied on the evolving separation area during the non-linear analysis. Leakage-sensitivity behaviour is evaluated through monitoring of the flange-gasket contact status and the extent of the separation area.

The methodology also incorporates elasto-plastic gasket material behaviour through bilinear plasticity models and accounts for bolt pre-tension variations due to thermal contraction. Validation of the modelling approach is performed using experimental data from literature through comparison of force-displacement response. The validated methodology is subsequently applied to a representative flange of the H2ELIOS cryogenic LH_2 tank.

3. Results / Conclusions

The developed modelling methodology demonstrates the capability to accurately represent the structural response of bolted flange joints under combined mechanical and thermal loading conditions. Comparison with experimental results from literature showed excellent

agreement in the predicted force-displacement behaviour, validating the applicability of the proposed approach for bolted flange assessment. Ongoing work focuses on the application of the developed framework to a representative LH_2 tank flange configuration for aerospace applications, with the objective of supporting lightweight and reliable cryogenic tank design.

Acknowledgement: The project H2ELIOS is supported by the Clean Aviation Joint Undertaking and its members, funded by the European Union. However, the views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them. The H2ELIOS LH_2 tank concept is protected under a patent owned by Aciturri.

Development of a Comprehensive Testing Infrastructure for Cryogenic Liquid Hydrogen Technologies in Aviation: Safety, Loading, and Performance Validation

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The transition toward zero-emission aviation has identified liquid hydrogen (LH2) as a primary candidate for future aircraft propulsion due to its high gravimetric energy density. However, the integration of cryogenic technologies into the aeronautical ecosystem presents significant challenges regarding infrastructure, operational safety, and performance evaluation. This study details the design and implementation of a dedicated testing infrastructure for cryogenic technologies, engineered to support the whole range of aerospace testing. The tests to be performed requires a complex premises involving safety considerations for staff members and surrounding areas, ATEX classified zones and cryogenic capabilities. Moreover, high precision instrumentation is required to reduce uncertainties for the determination of key parameters such as stress/deformation during ambient-temperature pull-downs and subsequent filling operations, temperature gradients of the test article and its subsystems, LH2 supply flowrate profiles, as well as dormancy and boil off.
In this work, **TNO Multi-Energy Method** was used to calculate safety distances and potential blast effects, ensuring risk mitigation within complex environments. Accordingly, the designed infrastructure has been located in **Lleida-Alguaire Airport** with a dual-purpose environment, intended to facilitate a seamless transition between **ground-based static tests and in-flight testing**. This testing infrastructure includes a **fully controllable cryogenic loading** system designed to maintain high safety standards during fuel transfer while enabling truthful measurement of performance parameters.
According to models used and terrain assumptions tanks up to 175kg LH2 could be tested with 250m safety distance. To mitigate heat ingress LH2 vacuum isolated pipes are used and supply is placed at a closer distance, safety is ensured by modifying the terrain topography. Safety studies including HAZID and HAZOP and results demonstrate that this integrated approach provides the necessary data and safety assurance required to accelerate the certification and deployment of hydrogen fuelled aircraft.
These facilities enable full-scale testing beyond laboratory environments, allowing higher Technology Readiness Levels (TRL) to be achieved, thereby bridging the gap between prototype to certification.

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Integrated SHM and Leak Detection Architecture for Composite LH_2 Aircraft Tanks

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[2] CIRA, Italy

1. Introduction / Objectives

Future hydrogen-powered aircraft require lightweight cryogenic storage systems that ensure both structural integrity and operational safety. Within the Clean Aviation project H2ELIOS, a novel conformal composite liquid hydrogen (LH_2) tank is being developed to enable efficient integration of hydrogen storage into future aircraft architectures. However, the combination of composite materials, cryogenic operation, and demanding aviation safety requirements introduces new challenges for structural monitoring and fault detection . To address these challenges, an integrated monitoring concept is being developed that combines Structural Health Monitoring (SHM), hydrogen leak detection, and system health monitoring within a common architecture. The objective is to provide continuous condition assessment, early fault detection, and enhanced operational safety through complementary sensing technologies tailored to cryogenic hydrogen storage systems.

2. Methodology

The proposed monitoring concept combines multiple sensing modalities within an integrated Health and Usage Monitoring System (HUMS) for composite LH_2 storage systems. Structural Health Monitoring is performed using a combination of SMA-based strain sensors and Fiber Optics (FO) sensors for Acoustic Emission (AE) sensing intended for event detection on the outer tank.

These complementary optical, acoustic, and electrical sensing approaches provide information on strain evolution, structural loading, damage initiation, and transient events associated with crack formation. The use of different sensing principles enables increased robustness and sensor diversity for monitoring complex composite structures operating under cryogenic conditions (see Figure 1). Hydrogen safety monitoring is realized through the combination of acoustic leak detection and hydrogen gas sensors. Acoustic sensing enables the detection of leak-related ultrasonic emissions, while hydrogen sensors provide direct measurement of gas concentration. The combined approach supports the detection of both incipient and larger leakage events while reducing the probability of false alarms. To complement structural and safety monitoring, MEMS-based inertial sensors are employed to monitor dynamic system behavior and long-term changes in structural response. The resulting architecture combines structural, safety-related, and dynamic monitoring information within a unified framework. The monitoring system is currently being integrated into an open-frame LH_2 tank demonstrator. Sensor placement, electronics integration, communication architecture, and monitoring strategies are adapted to the specific requirements of cryogenic composite storage systems and future aviation applications.

3. Results / Conclusions

Experimental investigations have demonstrated (see Figure 2) the feasibility of the individual sensing approaches under representative operating conditions, including cryogenic environments, structural loading scenarios, and leak-related events. The results indicate that optical, acoustic, electrical, and MEMS-based sensing technologies provide complementary information for reliable condition assessment of composite LH_2 storage systems.

The presented work demonstrates the potential of an integrated monitoring architecture combining SHM, hydrogen leak detection, and system health monitoring within a common framework. The ongoing demonstrator implementation provides a pathway toward the validation of integrated monitoring systems supporting the safe deployment of hydrogen storage technologies in future aviation applications.

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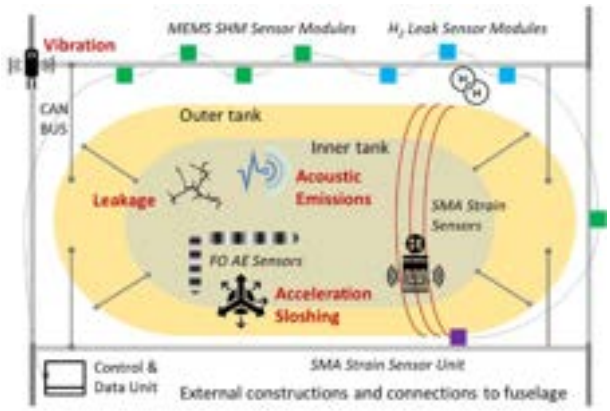


Figure 1. *Proposed monitoring concept*

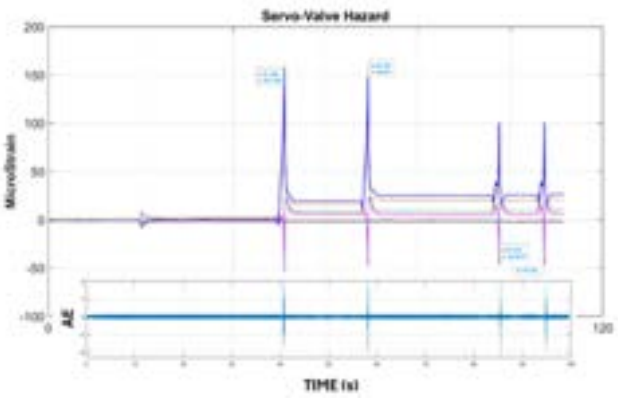


Figure 2. *The case of servo valve hazard: the output provided by different sensors*

State of the art for H2-air combustion & SOFC - Dynamic panel discussion

Chaired by:

Mr. Georgios Bampanis (European Climate, Infrastructure and Environment Executive Agency - CINEA)

HESTIA: Hydrogen combustion in aeroengines

Nicholas Treleaven, Marc Truscelli
SAFRAN Group, France

1. Introduction / Objectives

To reduce the climate impact of aviation, decarbonisation is a major challenge. Current aircraft engines burn hydrocarbon fuels such as kerosene or, more recently, emerging SAF products (Sustainable Aviation Fuels). Hydrogen is also considered as a promising fuel, but the burning of hydrogen creates radically new challenges that need to be understood and anticipated. The HESTIA project focused on increasing the scientific knowledge of hydrogen-air combustion for future hydrogen-fueled aero-engines. Different challenges are addressed in HESTIA: improvement of the understanding of turbulent hydrogen-air combustion, including preferential diffusion of hydrogen, modification of the turbulent burning velocity, thermoacoustics, NOx (Nitrous Oxides) emissions, and adaptation of optical diagnostics); assessment of innovative injection systems for H_2-optimized combustion chambers (flashback risk, lean-blow out, stability, NOx emission minimisation, ignition); and improvement of CFD tools and methodologies for numerical modelling of H_2 combustion in both academic and industrial configurations.

2. Methodology

The HESTIA project was completed in two phases: a first phase of basic research and a second phase of applied research; and three technical work packages. Both of these phases included experimental and numerical approaches including the interaction of complex and varied physical phenomena. The academic and basic research phase has investigated the three major research fields: understanding of H_2/air combustion key phenomena such as stabilization, flashback, ignition, pollutant emissions and heat transfer through fundamental experiments; flame dynamics of H2/air combustion to understand the response of H_2 flames to acoustics; and modelling of elementary processes involved in turbulent reactive flows of H_2/air mixtures. The applied research phase built upon the basic research phase to develop and consolidate experimental and numerical methods dedicated to design, and evaluated several H_2 injector concepts, first in lab-conditions, and then in aero engine representative conditions (equivalence ratio, pressure, temperature).

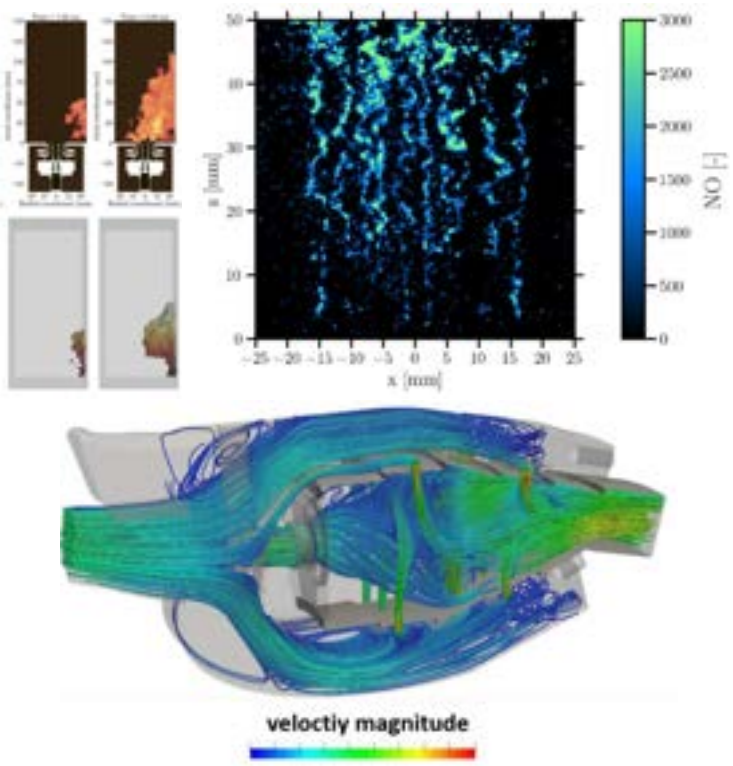


Figure 1. *Examples from each work package Left: Simulations of ignition of a swirl stabilized injector (WP1). Centre: Experimental measurements of NO produced by strut injectors (WP2). Right: MTU aeroengine baseline case (WP3).*

3. Results / Conclusions

An example of the some of the results produced is shown in Figure 1. Since the start of HESTIA in 2022, fundamental studies have brought a better understanding of H_2/air combustion. In particular, new modelling techniques have unlocked advanced multi-physics simulations adapted for the specificity of hydrogen, which, in turn, enables us to better capture relevant phenomena (e.g. flame stabilization, pollutants, etc.). Numerous lab-scale test rigs have been commissioned and are being used to test a wide variety of promising injectors. These experimental results will also constitute a pillar against which models and simulations can be validated. New diagnostics, new tools and, in general, best engineering practices have been transposed to hydrogen injectors — whether incremental improvements or breakthrough technologies. Furthermore, new archetypes of flames have been thoroughly investigated.

Integrated power and propulsion system based on hydrogen gas turbine and SOFC for clean aviation

Stefanie de Graaf[1], Panagiotis Laskaridis[2], Mauro Salazar[3], Mario L. Ferrari[4], Jan Zanger[1], Frederic Tong-Yette[5]

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[5]*SAFRAN Group, France*

1. Introduction / Objectives

Aviation's carbon footprint poses a critical challenge to global sustainability, with emissions soaring as air travel becomes increasingly prevalent. Traditional jet engines burn fossil fuels, releasing CO_2 and NO_X, exacerbating climate change. The urgency to decarbonise this sector demands innovative solutions. The EU-funded FlyECO project offers a pathway to low-emission air travel and sustainable growth. Through the integration of innovative technologies like solid oxide fuel cells (SOFC) and hydrogen as an energy carrier, the project targets a 50% reduction in NO_X emissions while eliminating CO_2 emissions altogether. Focusing on commuter and regional aircraft class propulsion systems, FlyECO aims to develop an integrated power and propulsion systems (IPPS) architecture. This work addresses the critical need for transformative technologies to curb aviation's environmental impact, advancing towards real-world implementation of hydrogen-based hybrid propulsion systems within the European strategic framework for clean aviation.

2. Methodology

FlyECO employs a comprehensive methodology centered on the simulation and evaluation of dynamic performance within a tightly coupled cycle-integrated hydrogen-based propulsion system of one megawatt. The consortium develops and matures transformative technologies for coupling and integrated operation of Gas Turbines (GT) and SOFCs. The approach encompasses an overall system assessment on the aircraft level, including detailed performance analysis across design and off-design conditions. Mechanical integration and transient simulation are utilized to ensure stability and efficiency during varying flight phases. A core component involves developing an overall controls approach to optimize power management and distribution of the IPPS. This strategy is validated through a cyber-physical demonstrator focusing on GT and SOFC coupling. The project executes a cyber-physical demonstration for validation of Technology Readiness Level (TRL) 3 of hydrogen combustion with steam ingestion. By combining advanced modeling with physical validation, the methodology ensures that power management and distribution strategies are rigorously tested. This multi-faceted approach facilitates the maturation of hybrid power architectures, bridging the gap between theoretical models and practical airborne application while adhering to strict safety and performance standards required for regional aviation propulsion. The simulation framework refines the integrated power and propulsion systems architecture, ensuring all components function cohesively under dynamic loads.

3. Results / Conclusions

FlyECO expects to achieve significant milestones in sustainable aviation propulsion. Key outcomes include the validation of TRL 3 for hydrogen combustion with steam ingestion, confirming the feasibility of zero CO_2 emissions and at least a 50% reduction in NO_X emissions. The project will deliver a validated cyber-physical demonstrator proving the integrated operation of GT and SOFC coupling. Furthermore, an optimized controls approach for power management and distribution will be established. Beyond technical deliverables, FlyECO contributes to the Horizon Europe impact assessment and supports the Governing Board of the Clean Aviation and Clean Hydrogen partnerships. A comprehensive technology roadmap for GT-SOFC hybrid systems will be published, alongside open-access datasets and models for the scientific community. These results pave the way for low-emission air travel, providing foundational technologies for deploying hybrid power systems in commuter and regional aircraft, supporting Europe's decarbonisation and sustainable growth goals.

Demonstration of Novel Kerosene-H2 Multi-Fuel Combustor

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[2]Ergon Research, Florence, Italy

1. Introduction

While H_2 is a promising fuel to decarbonize aviation and to reduce its climate impact, the transition to liquid hydrogen (LH_2) as a fuel is very difficult due to the humungous challenges faced in several aspects of hydrogen, right from H_2 production, logistics, refuelling, storage, fuel system, combustion, engine design, etc. Many of these challenges are being tackled in several EU projects but the practical usage of large quantities of LH_2 as a fuel remains uncertain, thereby forcing Airbus to postpone its ambition to bring an LH_2 aircraft to the market by 2035. The HOPE project takes a pragmatic approach and investigates a novel multifuel aircraft which uses both Kerosene and LH_2 so that the amount of LH_2 required for the mission is reduced substantially. This novel concept greatly eases the hurdle of using H_2 in aviation as such a multi-fuel aircraft can fly even to airports without LH_2 infrastructure. The current paper elucidates the design and testing of a multi-fuel, multi-phase burner that can operate with H_2 and kerosene flexibly while reducing emissions from the combustor.

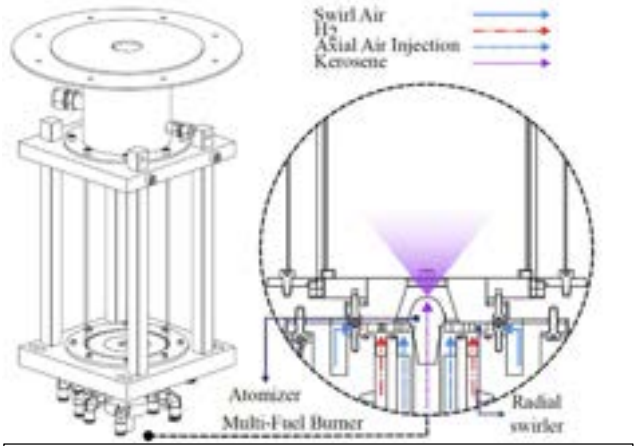


Figure 1. Sketch of the HOPE experimental

2.Methodology

Since the combustion characteristics of the two fuels are quite different, the combustor must be suitable to accommodate the variation in the fuel properties. The schematic of the combustor and the injector is shown in Fig. 1.The injector comprises four concentric flow paths, listed from the center outward: (1) a pressurized liquid kerosene supply feeding a SIMPLEX atomizer, (2) AAI holes for flashback suppression, (3) cross-flow injection of gaseous H2 into (4) a swirling air stream generated by a radial swirler. These flow streams merge in a converging tube that accelerates the mixture prior to entering the chamber, further decreasing the risk of flashback. Flame properties under varying Hydrogen Power Share (HPS) and Axial Air Injection (AAI) conditions are characterized using DSLR imaging, OH∗/CH∗ chemiluminescence, and kerosene-PLIF, with emissions measured using an exhaust gas analyzer.

3. Results and summary

As expected, variations in HPS significantly affect the combustion process, resulting in marked changes in the anchoring position and overall flame shape and length. These differences arise from a variety of strongly coupled mechanisms, including droplet evaporation, fuel-air mixing, and changes of flame speed. The relative contribution of these mechanisms to flame stabilization remains under investigation. In the present configuration, initial H_2 addition enhances spray-flame reactivity and reduces CO, while further increase in HPS improves fuel-air mixing and suppresses NO. At higher HPS (≳70%), deteriorating atomization induces a dual-flame structure that produces the least favorable emission characteristics, highlighting the importance of atomization strategy for extending low-emission operability at high H_2 substitution. As HPS approaches full substitution, combustion becomes H_2-dominated, the droplet-burning zone disappears, and both CO and NO decline to their lowest levels at HPS = 100%. Despite atomization-limited emission performance at high HPS in the present configuration, the results demonstrate the potential of synergistic and fuel-flexible Kerosene-H_2 combustion in a model combustor for stable, low-emission operation across a wide range of HPS.

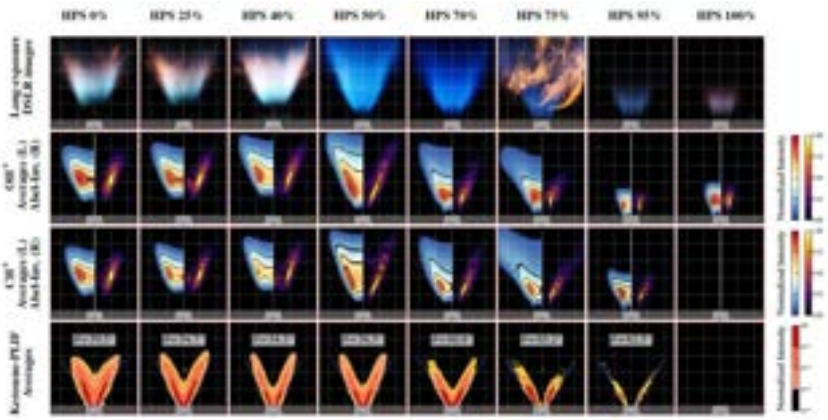


Fig.2: Effect of increasing HPS on flame and spray morphology at AAI = 20%. Columns show increasing HPS; rows (top–bottom) show long-exposure DSLR images, OH∗ ensemble-averages and Abel-inverted fields, CH∗ ensemble-averages and Abel-inverted fields and Kerosene-PLIF spray images.

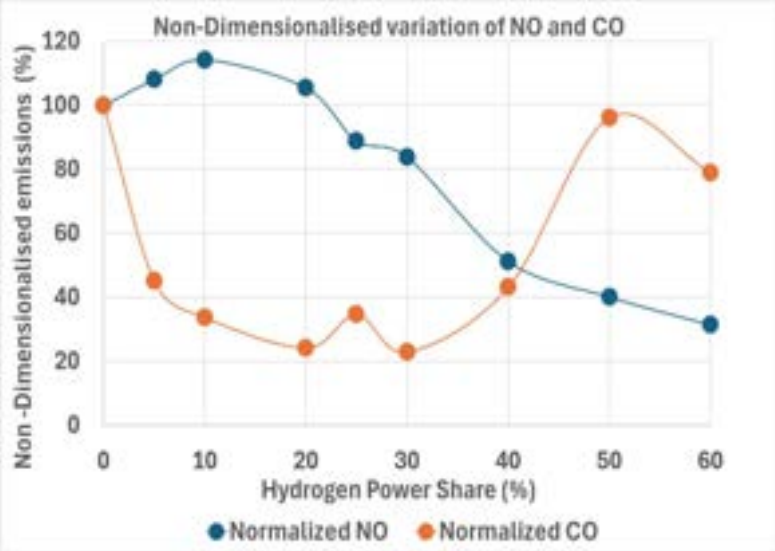


Fig.3. Normalized variations of NO and CO emissions with HPS

The variation of the normalized emissions with increasing HPS in the evaporation-controlled regime is shown in Fig. 3. As can be seen, both CO and NO reduce substantially with H_2 addition. The observed CO reduction results from enhanced reactivity and oxidation kinetics associated with H_2 addition, promoting more complete oxidation within the spray flame [2, 3]. As HPS increases further to 40%, CO rises from its minimum while NO decreases to ~50%, suggesting a shift in the underlying chemistry. As premixed H_2 begins to sustain combustion independently, heat release becomes spatially distributed, suppressing localized hot spots and leading to lower NO, consistent with the homogenization. CFD Simulations were also carried out to understand the combustion physics of this novel combustion regime better. Fig. 4 shows the time-averaged HRR from CFD compared with the experimental time-averaged Abel-inverted OH* chemiluminescence data. At HPS = 0.0 (pure kerosene), the flame front appears relatively widespread. This behaviour is primarily driven by the wide droplet-size distribution, which spreads the evaporation process over a fairly large range of diameters. As a result, fuel–air mixing in the gaseous phase becomes less localized, and the subsequent reaction zone extends over a wider volume. At HPS = 0.6, the multi-fuel configuration exhibits a flame topology like that at HPS = 0.0, but the flame is noticeably shorter due to the higher reactivity of hydrogen. The heat release tends to propagate through the Outer Recirculation Zone (ORZ) and attaches to the corners of the mixing-tube.

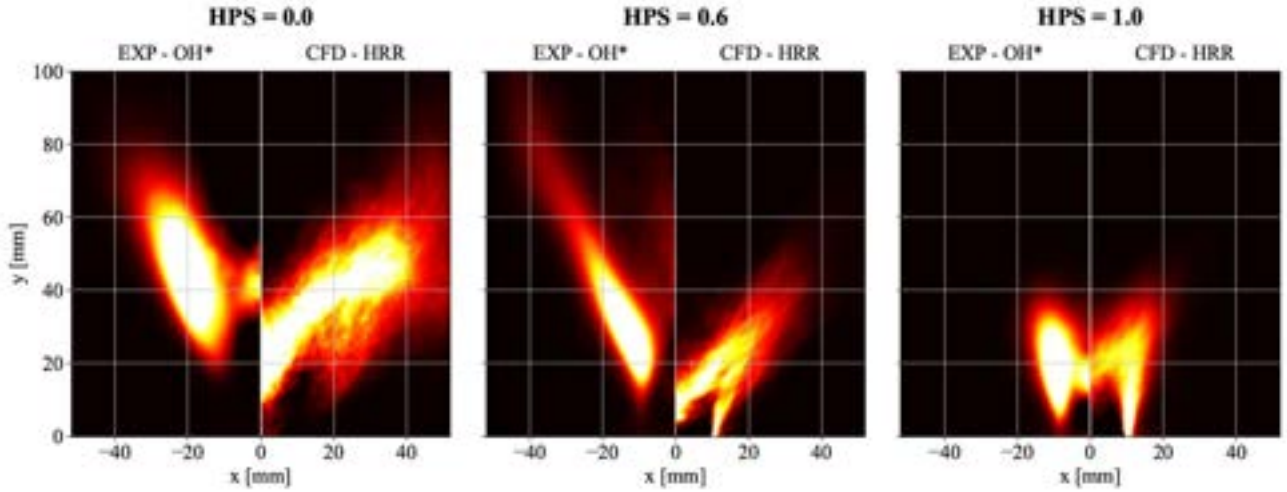


Fig. 4: Comparison between experimental Abel-inverted normalized OH* from experiments and normalized Heat Release Rate (HRR) from CFD.

Innovative and multi-disciplinary aircraft design for emissions reduction

Chaired by:
Prof. Emmanuel Benard (ISAE-SUPAERO, France) & Prof. Andreas Strohmayer (University of Stuttgart, Germany)

From General Aviation to Regional and SMR, evaluation of novel architectures and technologies for low-carbon air transport using the FAST-OAD aircraft design software

S. Defoort[1], E. Nguyen Van[1], E. Stragiotti[1], R. Parello[1], F. Lutz[2], S. Delbecq[2], E. Benard[2]
[1] ONERA, France
[2] ISAE-SUPAERO, France

1. Introduction / Objectives

At aircraft level, there are several levers to be activated to achieve the emission reduction targets, especially towards decarbonized aviation: introduction of advanced airframe technologies and architectures (such as laminar airfoils, extended use of CFRP, high aspect ratio wings potentially strut-braced, blended wing body,…), novel engine design and integration (ultra-high bypass ratio, unducted single fan, distributed propellers,…) and on top of that, use of new energy carriers such as electricity (with potential hybridization with thermal engine) or liquid hydrogen for direct burn or electricity generation through fuel cells. Many studies are currently addressing such technologies and their impact on the aircraft architecture, with sometimes high fidelity and detailed design. But providing a consistent evaluation of these future aircraft options and comparing them with each other and with

already flying solutions remains a challenge. In the frame of the Clean Aviation programme, ONERA and ISAE-SUPAERO have extended the capabilities of their in-house aircraft design framework FAST-OAD to apply it on several families of aircraft, from hybrid-electric general aviation and regional aircraft (HERA project) to short-medium range LH2 (SMR ACAP and UPWING projects). This paper will describe the OAD methodology followed, from code extension to definition of relevant reference aircraft and novel configurations.

2. Methodology

In order to achieve a consistent technology evaluation at aircraft level, a rigorous approach grounded on common and validated tooling is required. In this paper we will successively describe:

- The features, in particular modularity and extendibility, of the FAST-OAD software **Error! Reference source not found.**, an open source solution jointly developed by ONERA and ISAE-SUPAERO to perform aircraft sizing upon Top Level Aircraft Requirements, with application to CS-23 and CS-25 type of transport aircraft, with reference models of trainer, leisure, small commuter, Regional, and SMR aircraft families;

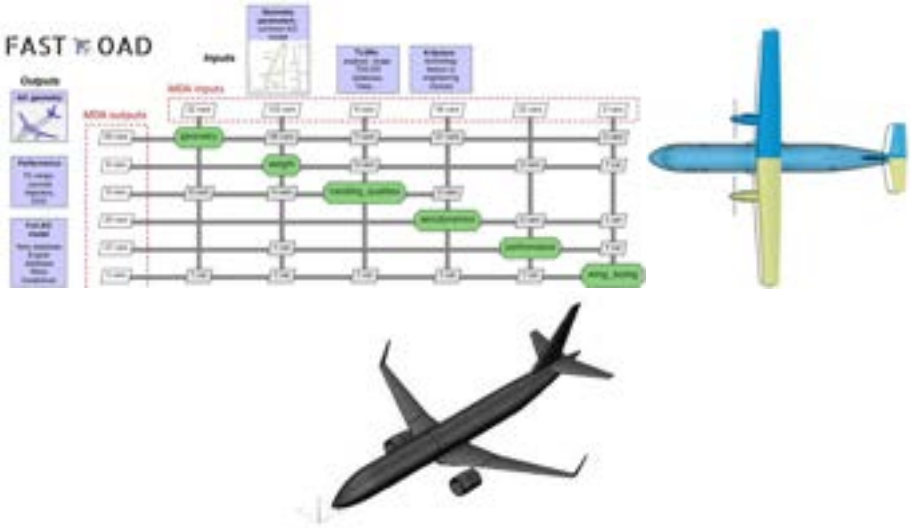


Figure 1. *FAST-OAD design structure matrix (left), regional reference (center), SMR reference (right)*

- The medium-fidelity modelling effort to enhance the framework towards novel technologies and architectures: hybrid-electric powertrain **Error! Reference source not found.**, hydrogen distribution and storage **Error! Reference source not found.**, aero-structural design of high aspect ratio wings, integration of new engine designs, demonstrating the flexibility of FAST-OAD towards more parameters and higher fidelity;
- The definition of relevant reference aircraft and their cross-comparison and validation against existing data and similar studies. More specifically, the RTA aircraft (similar to ATR-72) and the O239 (similar to A321) will be introduced;

- The exploration performed to identify promising solution for several energy carriers, engine options, airframe design, using advanced design of experiments and optimization capabilities.

3. Results / Conclusions

After modelling and validating reference aircraft with sufficient confidence (calibration under 1% error with respect to available data and studies, which will be illustrated in the paper) for regional and SMR aircraft, the FAST-OAD software can be used to study novel architectures for future low-carbon air transport. The final paper will describe the efforts toward a hybrid-electric regional aircraft conducted in the HERA project to support a common framework with European partners, and the engine and airframe options applied to LH2 SMR aircraft in the ACAP and UPWING projects. Perspectives towards a reference long range aircraft will be also introduced.



Figure 2. *Illustration of technology option studied: hybrid electric aircraft ingredients, LH2 strut-braced wing aircraft options*

Multifidelity overall aircraft design of a LH2-Powered Strut-Braced Dry-Wing Aircraft using surrogate models and design of experiments

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ONERA, France

1.Introduction / Objectives

To address aviation's rising contribution to global warming, the sector must transition towards carbon-free energy carriers such as hydrogen. Yet, challenges related to large-scale green hydrogen production and onboard liquid hydrogen storage remain significant. In this context, improving aircraft energy efficiency can substantially ease the transition toward more sustainable aviation. The Clean Aviation SMR ACAP project investigates the benefits of

several innovative technologies for a hydrogen-powered small-to-medium-range aircraft (239 passengers, 2,500 Nm). Within this framework, ONERA studies a high-aspect-ratio Strut-Braced Wing aircraft powered by hydrogen open-fan engines, with cryogenic hydrogen tanks integrated in the rear fuselage. The high aspect ratio, enabled by a dry-wing design and strut support, enhances aerodynamic efficiency, while the open-fan architecture improves propulsive efficiency. This study focuses on an Overall Aircraft Design approach to study the aero-structural trade-offs associated with the SBW configuration, assess its potential benefits and evaluate the sensitivity of aircraft performance to key design parameters.

2.Methodology

The SBW aircraft design was developed using FAST-OAD , an Overall Aircraft Design sizing framework based on OpenMDAO and jointly developed by ONERA and ISAE-SUPAERO. The study explored a design space centered on the geometry of the strut-braced wing, including the potential use of a jury strut to prevent strut buckling. The impacts of hydrogen tank integration and open-fan propulsion were fixed based on results from parallel Clean Aviation and internal projects.

To accurately assess high-aspect-ratio SBW configurations, new aerodynamic and structural models were developed, as the historical low-fidelity models available in FAST-OAD were not suitable for such architectures. High-fidelity RANS simulations, including a body-force representation of engine airflow, were performed to estimate aircraft aerodynamic drag polars and buffet constraints. In parallel, a finite-element aeroelastic model was developed to size the wing, strut, and potential jury strut structure, while accounting for dedicated load-alleviation strategies.

Because these high-fidelity models were computationally expensive, their integration into FAST-OAD relied on surrogate models for each discipline. Previous studies had already identified the main sensitivities of the concept to wing aspect ratio, sweep angle, and strut parameters . Consequently, the present work focused on the most promising regions of the design space to evaluate SBW performance with reduced uncertainty. This was achieved through an adaptive surrogate-enrichment strategy derived from the EGMDO methodology, in which new sample points were selected using an Expected Improvement criterion optimized with SEGOMOE . The objective was to determine, with limited uncertainty and minimal calls to high-fidelity simulations, the optimal wing and strut geometry minimizing aircraft energy consumption over a representative 800 Nm mission, while assessing the potential need for a jury strut.



Figure 1. *Design of experiments to assess effect of wing parameters (left); Hydrogen Powered Strut-Braced-Wing Aircraft (right).*

3. Results / Conclusions

The results provide an overview of the performance of the strut-braced wing concept, revealing a substantial reduction in energy consumption that can be directly related to the detailed analysis of the associated drag reductions. The optimization process clearly highlights the aero-structural trade-offs governing the configuration. Although the optimal design was obtained using a limited number of high-fidelity simulations, the intelligent design-space exploration and adaptive surrogate-enrichment strategy enabled a controlled level of uncertainty regarding both the predicted aircraft performance and the optimality of the final solution.

LH2-Powered Strut-Braced Dry-Wing Aircraft: Aero-Structural Benefits and Challenges

M. Méheut[1], D. Losada Costoso[1], F. Moens[1], O. Atinault[1], G. Starck[1], C. Julien[1], L. Vertonghen[1], C. Mollet[1], S. Defoort[1], E. Nguyen Van[1], E. Stragiotti[1], R. Parello[1], J. Sodja[2], S. de Boer[2]

[1] ONERA, France

[2] Delft University of Technology, Netherlands

1. Introduction / Objectives

The aviation sector aims to reduce carbon emissions and enhance energy efficiency. Innovative concepts, such as high aspect ratio wings and novel energy sources, are gaining prominence. In the Clean Aviation UP Wing project, ONERA and TU Delft investigate a High Aspect-Ratio Dry-Wing concept for a Small-Medium-Range mission (2500 Nm, 239 PAX, Mach 0.78). The objective is to minimize flight energy consumption while achieving zero CO2 emissions. Liquid hydrogen (LH2) storage in the fuselage enables a dry-wing design, removing fuel weight from the wings. This paradigm shift allows for radical structural layouts. The study specifically focuses on the Strut-Braced Wing configuration to optimize the aero-structural compromise, aiming to support sustainable aviation transition.

2. Methodology

This research employs a multidisciplinary and multi-fidelity process to design the Strut-Braced Wing configuration. The process begins by defining key design variables to explore the design space effectively, focusing on the impact of critical design parameters on overall performance. Disciplinary modules based on high-fidelity simulations (RANS for aerodynamics and Finite Element Model for structural sizing) are integrated into the overall design loop to assess aerodynamic, structural, and performance metrics simultaneously. The design space exploration targets a Small-Medium-Range mission profile (2500 Nm, 239 PAX, Mach 0.78).
A critical aspect involves managing the LH2 storage constraints. Since liquid hydrogen is stored in dedicated cryogenic systems within the fuselage for safety and efficiency, the wing becomes a "dry" structure. This eliminates the traditional fuel weight relief, necessitating a re-evaluation of load cases and structural design. To achieve very high aspect ratios without prohibitive weight penalties, the addition of a strut is analyzed as the primary solution to reduce induced drag significantly with a limited weight penalty. The impact of a jury strut is also investigated.

The methodology includes aerodynamic assessment via CFD-RANS simulations and post-processing using far-field drag breakdown modules. Structural optimization is based on detailed Finite-Element Models to minimize the mass of the configuration including dedicated load alleviation strategies. The study systematically evaluates the trade-offs between drag reduction, structural weight, and overall aircraft performance across a large design space (including the presence of a jury strut, wing aspect ratio and swept angle as well as several strut parameters). The analysis ensures a robust evaluation of the innovative strut-braced layout for future LH2-powered aircraft.

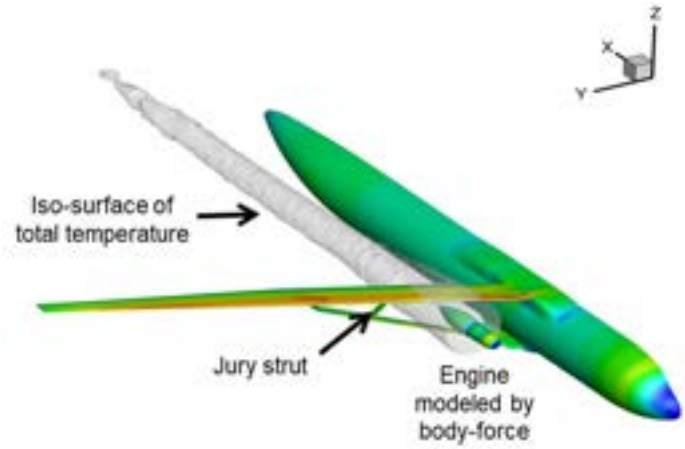


Figure 1. *Strut-Braced Dry-Wing Concept*

3.Results / Conclusions

The findings of this study provide valuable insights into the potential of the Strut-Braced dry-wing configuration for LH2-powered aircraft. By exploring the aero-structural benefits and challenges of this specific design, the research highlights the impact of critical design parameters, particularly the wing aspect ratio and strut integration, on overall performance. The analysis demonstrates significant induced drag reduction while managing structural weight penalties effectively. These results are expected to inform future design decisions, contributing to the development of more efficient and sustainable aviation solutions.

Preliminary design of a future SMR aircraft powered by LH2 Open Fan engine

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[1]ONERA, France
[2]Safran Group, France

1. Introduction / Objectives

In the search for a reduced carbon footprint of aviation, several levers are available to lower emissions and improve the global energy efficiency of flight. At the aircraft level, the engine is one of the key drivers of the energy consumption and several concepts are being studied

for the next generation of aircraft. Additionally, the shift to liquid hydrogen (LH2) as primary fuel for the engine is one of the pathways studied to ensure zero carbon emission in flight. In the frame of the Clean Aviation SMR pillar, the OFELIA project is dedicated to the technology maturation of an Open Fan engine concept, while the SMR ACAP project proposes aircraft configurations tailored to specific wing and engine technologies, using SAF or LH2 as a fuel. In this framework, ONERA and Safran Aircraft Engines have been collaborating to study a LH2-powered SMR aircraft concept designed for a 2500 Nm, 239 PAX mission, Safran being in charge of the preliminary design of the Open Fan LH2 engine from thrust requirements, and ONERA in charge of the Overall Aircraft Design using the engine characteristics as inputs.

2. Methodology

In order to achieve a consistent engine-aircraft matching, an iterative process has been defined between Safran and ONERA.

- As a first step, architecture and technology assumptions for the aircraft have been defined. The concept is a LH2 direct burn aircraft using two caudal tanks, with 8-pax-abreast cabin layout to limit the fuselage length. As the integration of LH2 systems brings significant mass and drag penalty, a high aspect ratio wing is chosen to improve the aerodynamic efficiency, combined with a strut-braced high wing concept enabling both an easier engine integration and a better structural efficiency. Conducting a first OAD sizing provides an initial set of thrust requirements for the engine.
- Using these requirements, a first engine design is performed to calculate available thrust and SFC on a reduced set of flight points representative of the aircraft trajectory. The pre-sizing provides also an estimate of engine mass and size, as well as nacelle drag. To allow fine-tuning of the matching with the aircraft, sensitivities to the Take-off Thrust and Top-of Climb thrust requirements are computed, enabling the rubberization of the engine.
- Using a multi-fidelity kriging surrogate model, the complete engine map is integrated into the ONERA FAST-OAD software dedicated to aircraft design, and an optimization process is conducted to find the combination of design parameters that minimizes the energy consumption on a typical mission of 800 Nm, while satisfying take-off distance and time-to-climb constraints. This provides updated thrust requirements for the final engine design.
- As a last iteration, the engine design is fine-tuned to the refined aircraft requirements and a final OAD evaluation is performed to compute the consolidated performance of this new Open Fan LH2 aircraft concept.

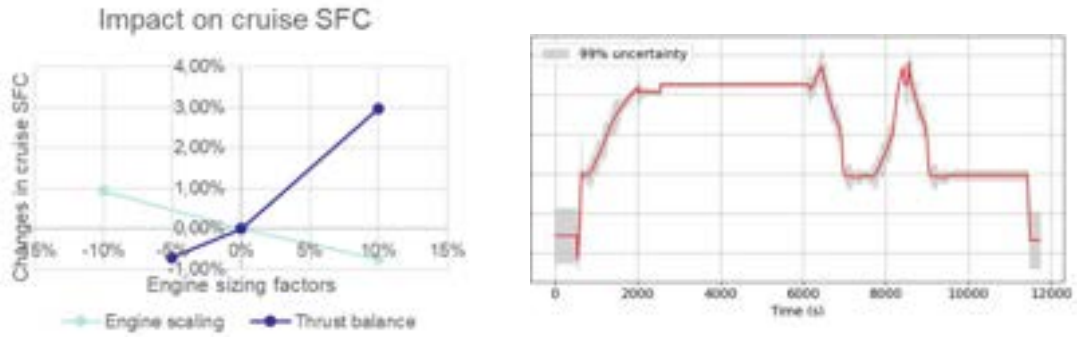


Figure 1. *Sensitivity of the engine SFC to thrust requirements (left), integration of design spot points in a full trajectory computation (right)*



Figure 2

3. Results / Conclusions

Thanks to an iterative process between overall aircraft design and engine pre-sizing, this study provides a consistent view of what could be a LH2 powered SMR aircraft using an ultra-efficient open fan engine concept with direct LH2 burn. Optimizing the configuration upon the first parametric engine sizing results leads to an optimal matching of the engine to the thrust requirements along the trajectory, and demonstrates an energy saving of around **-15%** with respect to current generation of aircraft, while maintaining zero CO2 emissions in flight.

Nonlinear Aeroelastic Wingbox Sizing Model for Overall Aircraft Design of Flexible High-Aspect-Ratio Wings

Ousmane SY, Joseph Morlier, Emmanuel Benard
ISAE-SUPAERO, France

1. Introduction / Objectives

The growing demand for more fuel-efficient and sustainable aviation has renewed interest in high-aspect-ratio (HAR) wings due to their ability to reduce induced drag and improve fuel efficiency. However, HAR wings also introduce significant structural and aeroelastic challenges, including increased structural weight caused by higher bending moments,

geometrically nonlinear behavior, and greater susceptibility to aeroelastic phenomena such as flutter due to their high flexibility.

On the overall aircraft design methodology front, traditional aircraft design methods and tools are often inadequate for the sizing and exploration of HAR wing concepts. Existing wing weight models traditionally rely on empirical correlations derived from conventional wings and therefore cannot capture the strong aerostructural coupling, nonlinearities, and aeroelastic behavior inherent to high-aspect-ratio wings. This work addresses these limitations by developing a mid-fidelity nonlinear aeroelastic wingbox sizing model based on a physics-based approach, intended for integration into an OAD framework for the preliminary design of flexible high-aspect-ratio wings.

2. Methodology

The proposed approach couples the nonlinear aeroelastic model implemented in SHARPy with a stress- and buckling-driven wingbox sizing methodology based on thin-walled beam theory . Figure 1 illustrates the overall wingbox sizing methodology. Starting from the wing geometry and an initial thickness distribution, SHARPy performs aeroelastic analyses for the 2.5g and −1g maneuver cases, as well as a 1-cosine gust load case. The resulting critical load envelope is then used to size the wingbox components. Following aerostructural convergence, a flutter clearance check is performed, and the structural thicknesses are updated if necessary to prevent flutter instability.
The aeroelastic model is then integrated as a wing weight model into the FAST-OAD to enable the overall aircraft design of regional HAR wing aircraft.

3. Results / Conclusions

The sizing methodology is applied to a representative regional transport aircraft featuring a high-aspect-ratio wing. The results to be presented at the conference include the validation of the aeroelastic wingbox sizing model against existing empirical and physics-based wing weight models. A sensitivity analysis of the wing weight and structural properties with respect to aspect ratio is also performed. Finally, a complete OAD sizing of a regional aircraft using the integrated framework is carried out and compared with the existing OAD framework, including an assessment of the computational cost.

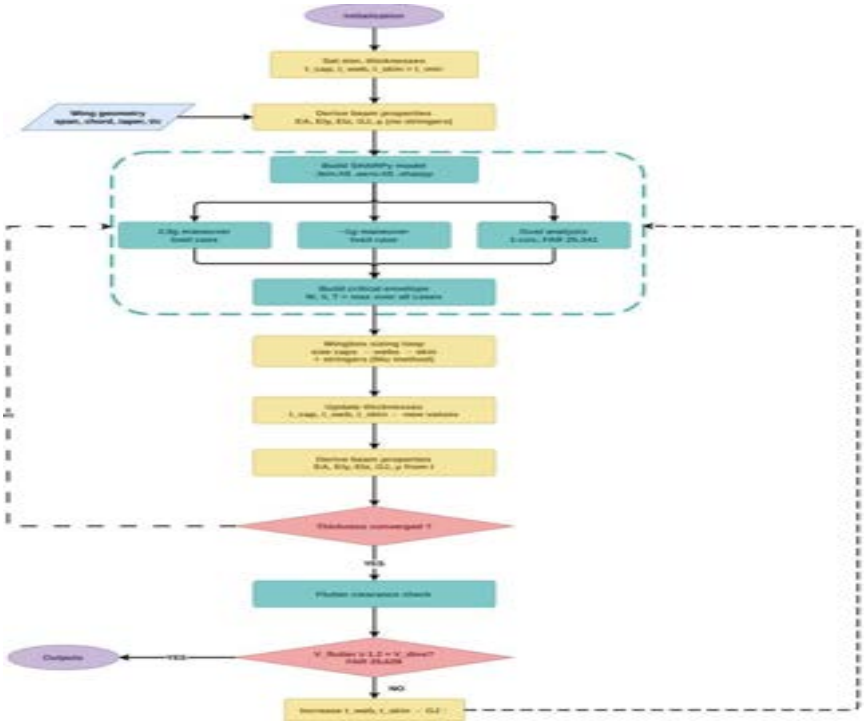


Figure 1. *wingbox sizing methodology*

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Flight Mechanics-Driven Conceptual Design of Twin-Fuselage Aircraft

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Universidad Politécnica de Madrid, Spain

1. Introduction / Objectives

The need to reduce aviation's environmental impact is the main driver of innovation within the aeronautical sector. Increasing concerns over climate change, combined with sustained growth in air transport demand, have motivated advances in materials, aerodynamics, propulsion, sustainable fuels, and operations aimed at lowering emissions and noise. Nevertheless, further gains from conventional Tube-and-Wing aircraft are becoming limited as technological maturity increases, leading to growing interest in unconventional aircraft configurations with potential for step-change improvements.

Among these, Twin-Fuselage layouts represent a promising yet underexplored solution, highlighting the need for dedicated conceptual design methodologies to assess their viability and justify further investment. While existing methods address initial sizing and weight estimation , the influence of flight mechanics on Twin-Fuselage design remains insufficiently explored . This work aims to address this gap by deriving configuration-specific design criteria

based on stability and controllability requirements, integrating airworthiness constraints into the conceptual design of Twin-Fuselage aircraft.

2. Methodology

To bridge the gap between flight mechanics and conceptual design, the flight dynamics equations of a Twin-Fuselage aircraft are analytically derived by expressing the inertia tensor as a function of the individual fuselage inertias and their relative separation. This formulation enables a direct assessment of the impact of fuselage separation on the dynamic behavior of the aircraft. In particular, fuselage separation is shown to significantly influence lateral stability and controllability, affecting the roll subsidence mode and reducing available lateral control authority.

A simplified one-degree-of-freedom representation of the roll subsidence mode is then employed to derive analytical expressions for its time constant, as well as for the minimum required lateral control power. The MIL-F-8785C standard is used to determine acceptable limits for these dynamic parameters, linking flight dynamics performance to handling qualities requirements, and enabling the definition of quantitative sizing criteria for lateral control surfaces and fuselage separation.

Additionally, CS-25 Subpart B airworthiness requirements, together with the associated Acceptable Means of Compliance, are used to define the required roll performance in representative flight conditions. These performance requirements are subsequently translated into constraints on lateral control authority, enabling the formulation of flight-mechanics-driven Twin-Fuselage design criteria.

This combined approach enables the integration of stability and controllability constraints from the early stages of the design process, improving the robustness and reliability of Twin-Fuselage conceptual design methodologies.

Finally, the proposed criteria are applied to a case study of a Twin-Fuselage aircraft defined under the same top-level aircraft requirements as the D300-XRF1 reference model . This reference corresponds to a long-range, high subsonic transport aircraft with a capacity of between 200 and 400 passengers, consistent with the design space of interest for Twin-Fuselage aircraft identified in previous studies.

3. Results / Conclusions

Twin-Fuselage-specific dimensioning criteria are defined by applying airworthiness regulations to the lateral stability and controllability characteristics of Twin-Fuselage aircraft, including the maximum fuselage separation and the aileron initial sizing.

Application of the proposed criteria to the case study indicates that the concept obtained using the current state-of-the-art initial sizing method requires redesign to satisfy flight mechanics constraints. This result highlights the importance of incorporating such criteria into early-stage conceptual design, ensuring compliance with airworthiness regulations and acceptable handling qualities, and reducing the risk of costly modifications in later design phases.

Box-Wing as a scalable enabling architecture from large transport to low-altitude economy

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1. Introduction / Objectives

Future aeronautical systems are increasingly shaped by functional requirements that cannot be addressed solely through incremental airframe refinements: capacity under infrastructure constraints, alternative-energy integration, electrified regional operations, and compact platforms for logistics, monitoring, and mobility. The latter domain is gaining relevance as a low-altitude economy, where urban air transportation, unmanned aerial systems, and smart-city services create new mission needs and operational constraints. Within this context, the box-wing is considered here not as a generic competitor to conventional aircraft, but as a scalable lifting architecture whose closed system can enable different functions across different aircraft classes. Building on a consolidated body of multidisciplinary studies, this work frames the box-wing as a cross-scale technology enabler, from medium-size transport aircraft to regional, commuter, amphibian, UAV, and eVTOL platforms, identifying the functions enabled at each scale and the collaborative research paths that could support future breakthrough aviation programmes.

2. Methodology

The work is structured as a critical, application-oriented synthesis rather than as a conventional review. The adopted logic is function-driven: the box-wing is read as an architectural platform whose closed lifting system may support different roles depending on scale, mission, requirements and constraints. For medium and large transport aircraft, the discussion focuses on span-constrained payload growth, aerodynamic efficiency, structural integration, and the accommodation of alternative energy carriers, including liquid hydrogen. For regional and commuter aircraft, the emphasis moves to load redistribution and optimization, airframe-power integration, and the possibility of coupling lifting-system efficiency with hybrid-electric or electrified propulsion. For amphibian, UAV and eVTOL platforms, the analysis is centred on compactness, geometric redundancy, low speed safety, and the possible functional separation between vertical lift and cruise propulsion for low-altitude missions. The methodological basis is therefore used as support for the functional argument. Previous physics-based conceptual design studies, aerodynamic and aeromechanic assessments, FEM/DoE-based structural surrogate models, multifidelity aerodynamic assessments, mission simulations, and impact analyses are not treated as a mere list of tools, but as evidence that the same architecture can be evaluated across different aircraft classes. The conceptual scheme in Figure 1 summarizes this cross-scale interpretation by connecting vehicle classes, enabled functions, and the assessment loop required to translate architectural potential into credible preliminary-design evidence. Rather than being limited to incremental performance gains over conventional configurations, the box-wing architecture is here interpreted as an enabling airframe concept, capable of opening design functions, integration strategies, and mission-specific objectives that are not fully captured by classical like-for-like comparisons.

3. Results / Conclusions

The expected contribution is a functional design map that positions the box-wing as a family of scalable airframe solutions rather than as a single aircraft concept. For larger aircraft, its value lies in combining aerodynamic efficiency connected to unique payload capability, together with advanced structural integration and alternative-fuel accommodation under infrastructure constraints. For regional aircraft, the architecture supports a tighter coupling between airframe, energy and power systems, and mission-level performance. For UAV and eVTOL applications, the most promising role is in the emerging low-altitude economy, where compactness, payload integration, redundancy, VTOL-cruise separation, safety, and mission flexibility are central design drivers; in this regard, a consolidated amphibious configuration and a novel lift-and cruise prototype are already undergoing scaled flight testing, see Figure 2. This framing is particularly relevant to EASN because it links aircraft design to operations, urban/peri-urban services, logistics, monitoring, and collaborative aerospace programmes, providing a basis for multidisciplinary agendas oriented toward future low-altitude and sustainable aviation research.



Figure 1. *Cross-scale role of the box-wing architecture as an enabling platform from transport to low-altitude-economy applications.*



Figure 2. *IDINTOS scaled flying model and full scale demonstrator (left); lift-and-cruise configuration for low altitude economics*

Hydrogen Tank Integration Trade-Offs for a Fuel Cell-Powered Business Commuter Aircraft

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1. Introduction / Objectives

Hydrogen fuel cell propulsion is a promising pathway for reducing the climate impact of short-range air transport, but its feasibility is strongly conditioned by the integration of cryogenic hydrogen storage. This issue is particularly critical for small CS-25-class aircraft, such as business jet / fast commuter configurations, where available fuselage volume is limited and tank mass, insulation thickness, dormancy requirements, and geometric constraints directly affect aircraft sizing and performance. The present work investigates aircraft-level trade-offs associated with the integration of liquid hydrogen tanks on the Piaggio PZero concept, a 19-passenger commuter / business aircraft designed around a 500 nm mission, Mach 0.54 cruise target, and hydrogen fuel cell powerplant architecture. The objective is to quantify how tank technology, dormancy time, venting pressure, and fuselage cross-section constraints influence the aircraft design.

2. Methodology

The aircraft-level analyses are performed with JPAD, the in-house conceptual aircraft design framework developed at UNINA. JPAD combines semi-empirical aircraft design methods with a flexible representation of non-conventional propulsion architectures, enabling the assessment of conventional, hybrid-electric, and fully electric configurations. The reference configuration is based on the PZero aircraft, a notional aircraft developed within the context of the HERA[3] work package dealing with hydrogen and fuel cell technology scalability. In the present trade-off study, the aircraft configuration is resized by varying the wing planform area and the installed fuel cell power to recover compliance with the project TLARs. The fuselage length, and diameter eventually, are updated as a consequence of the hydrogen tank sizing.

Cryogenic tank sizing is performed through a MATLAB-based tool. The tool estimates tank mass, external dimensions, insulation thickness, and gravimetric index for non-integral cylindrical tanks with hemispherical heads. Two tank technologies are considered: a double-wall vacuum-jacketed configuration with multi-layer insulation, and a single-wall foam-insulated configuration. The parametric database used to support aircraft-level studies covers hydrogen masses from 170 to 400 kg, dormancy times from 3 to 12 hours, venting pressures from 2.0 to 6.5 bar, and a reference inner tank diameter of 1.4 m. Instead of directly coupling JPAD with the MATLAB tank tool, the aircraft sizing workflow uses surrogate models trained on hundreds of tank analyses. These surrogate models provide tank mass and external volume as functions of hydrogen quantity, tank technology, dormancy requirement, venting pressure, and maximum allowable fuselage cross-section dimensions.

[3] HERA project (*Hybrid-Electric Regional Architecture*, Clean Aviation, GA ID: 101102007): https://project-hera.eu/home

3. Results / Conclusions

Preliminary tank-level results already show clear trends that will drive the aircraft-level trade-off study (

Figure **26**). For the vacuum-jacketed MLI tank, dormancy time has a limited influence at high venting pressures, while it becomes more critical at low venting pressures, especially in the 2–3 bar range. Under the considered geometric constraints, the MLI solution remains compliant over a broad range of operating conditions. Conversely, foam insulation shows a stronger sensitivity to dormancy time and often leads to excessive tank diameter or very large insulation thickness, particularly for dormancy periods of seven hours or more combined with low venting pressures. The analyses also indicate that venting pressure can significantly affect MLI tank performance, with gravimetric index values below 30% in several cases. Nevertheless, these preliminary results suggest that MLI-based storage is the most promising option for compact aircraft integration.

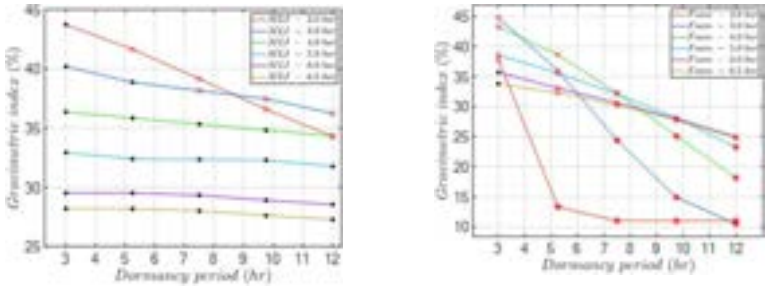


Figure 26. *Parametric study results obtained by varying dormancy requirement and venting pressure, assuming a constant tank inner diameter of 1.40 m and a hydrogen mass of 400 kg. Red cross symbols indicate tank designs exceeding the 1.65 m overall diameter limit, corresponding to the maximum fuselage diameter of the PZero baseline configuration. Asterisk symbols indicate designs exceeding both this diameter limit and the imposed insulation thickness limit of 0.5 m.*

Validation of an aircraft design framework with experimental flight test data of an all-electric aircraft

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1. Introduction / Objectives

Battery-electric aircraft are a promising way of reducing emissions for general aviation aircraft. The flying demonstrator e-Genius, designed and build by the Institute of Aircraft Design of the University Stuttgart, has showcased this many times. However, overall aircraft design frameworks or aircraft performance calculation tools oftentimes use empirical correlations, based on conventional aircraft. If models use physics-based simplifications, the correctness is not always/generally validated. Furthermore, while calibrating these tools for

the e-Genius it became apparent, that additional information from flight testing especially thrust and torque is necessary to fully validate these models and to achieve higher accuracy. Therefore, this work aims at validating the framework RCAIDE for the e-Genius in a battery-electric configuration using real flight test data.

2. Methodology

The preliminary aircraft design tool RCAIDE can be seen as a successor of the SUAVE tool which is also used in an in-house version at the institute. To compare the results of the model with flight test data the aircraft is newly equipped with an in-flight thrust and torque measurement. This allows to fully characterize the powertrain, measure its efficiency in different flight phases and also extract aerodynamic parameters. Thus, all three main aspects of aircraft design are covered, namely, aerodynamics, propulsion and mass.
For the aerodynamic model of the e-Genius, the built-in vortex lattice method of RCAIDE is used. Propeller performance is estimated with the blade element momentum theory solver available in the tool, and the propulsion system (energy network in SUAVE/RCAIDE) is based and adapted on available components. Mass is a given in this case, as the take-off mass of the aircraft is known and any modifications can be derived based on known masses of the components to be installed.
The work will focus in the first step on the isolated components and models. Therefore, generating an understanding of the accuracy of the underlying methods in isolation. In the next step the aircraft model is put together, moving to a global picture, investigating a full mission from takeoff to landing. This showcases how uncertainties from the isolated models propagate to the overall aircraft performance estimation. Therefore, a reference mission is selected and rebuilt in the framework. Ultimately, calibration factors can be derived for this aircraft to increase overall accuracy.

3. Results / Conclusions

The above work will give an understanding on the accuracy of the design tool for the e-Genius. In-flight measurement of torque and thrust will allow to characterize the full power train from energy source to the thrust generation including all (grouped) efficiencies along the way. Together with the mass of the aircraft and aerodynamic properties all aspects of the aircraft performance can be modeled. This includes aerodynamics, propulsion, and mass. Furthermore, these improvements will allow for a better extrapolation for new missions based on the derived calibration factors. In addition, it allows comparisons to higher-fidelity methods in the future to see their impact, but also include new technologies into the framework and estimate any performance impact this might have. By this, new technologies can be directly assessed within the framework, allowing to estimate benefits beforehand, and later assess the model accuracy and calibrate it.

Eco-Design of Mixed-Flow Turbofan Engines for Sustainable Supersonic Transport: Balancing Propulsive Performance and Emissions at the Conceptual Design Stage

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1. Introduction / Objectives

Following Concorde's withdrawal from service in 2003, commercial supersonic transport has been absent from civil aviation, mainly due to unresolved environmental issues, regulatory barriers, and social concerns. Nevertheless, interest in high-speed air travel has re-emerged over the past decade, fostering new research on low-boom and environmentally sustainable supersonic configurations. Within this context, the European H2020 MORE&LESS project established the scientific and methodological basis for the integrated design and multidisciplinary assessment of such aircraft. Building upon this legacy, the present work integrates combustion simulations and emissions analysis into the preliminary propulsion-system design process, proposing an eco-design methodology for turbofan engines intended for long-range supersonic transport. The study focuses on the redesign of a mixed-flow turbofan for a Concorde-like vehicle cruising at Mach 2 above 15 km, aiming to minimise both Thrust-Specific Fuel Consumption (TSFC) and pollutant emissions during supersonic cruise.

2. Methodology

The proposed methodology extends the preliminary engine design process established in the literature by incorporating detailed combustion simulations performed using the Cantera chemical-kinetics library. This allows for improved performance prediction accuracy and a quantitative characterisation of the emissions footprint. Both conventional Jet-A fuel and an Alcohol-To-Jet (ATJ) biofuel are considered as candidate propellants. Starting from the thrust requirement defined for the reference supersonic cruise design point, two complementary modelling layers are integrated into the propulsion eco-design framework. The first layer performs thermodynamic cycle analysis and preliminary optimisation of the propulsion system configuration presented in Figure 1, based on the evaluation of chemical equilibrium conditions in the combustion chamber. This layer integrates a constrained multi-objective optimisation routine targeting key design variables, simultaneously minimising TSFC and NO_x Emission Index ($EINO_x$), subject to thermodynamic, structural, and thrust constraints. While scientifically grounded, the first layer presents two key accuracy limitations: (i) the combustion model relies on chemical equilibrium rather than finite-rate kinetics, preventing a rigorous assessment of NO_x, CO, and unburned hydrocarbon (UHC) formation pathways; and (ii) the mixing process is modelled under the assumption of fully gaseous reactants, neglecting fuel phase change and assuming adiabatic conditions. The second layer focuses on the in-depth analysis of the optimal configuration identified by the first layer and on the optimised design of the combustion chamber. It directly addresses the accuracy limitations of the first layer by introducing two refinements:

- an enhanced combustion modelling strategy capable of incorporating not only thermodynamic effects but also chemical-kinetic aspects in the assessment of

pollutant emissions. Specifically, the chemical equilibrium assumption is replaced by 0D/pseudo-1D chemical-kinetic simulations using a Chemical Reactor Network (CRN) model, combining Perfectly Stirred Reactors (PSRs) and Plug Flow Reactors (PFRs). To address flame stability issues arising under lean mixture conditions, a Rich-burn, Quick-quench, Lean-burn (RQL) combustion strategy is implemented. The air distribution across the different combustor zones is optimised to simultaneously minimise NO_x and CO emissions.

- a dedicated routine for simulating the phase change of the injected fuel (atomization, vaporization), and the subsequent fuel–air mixing.

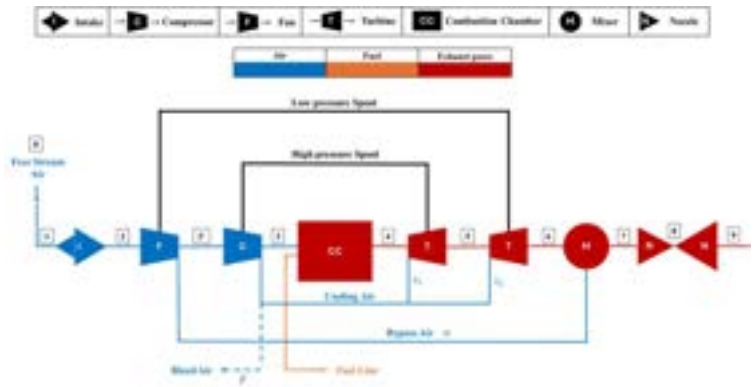


Figure 1*. Propulsion system scheme*

3. Results / Conclusions

This paper presents a physics-based, systems-level eco-design methodology for supersonic propulsion systems, integrating thermodynamic optimisation and combustion simulations within a unified modelling framework. The integrated framework delivers optimised propulsive design variables, air injection strategy, detailed thermodynamic cycle states, preliminary engine sizing, and a quantitative characterisation of the emissions footprint at the supersonic cruise design point. For the optimised Concorde-like engine configuration delivering 35 kN of thrust under Mach 2 cruise conditions at 16 km altitude, the computed Emission Indices are on the order of 15 grams per kilogram of fuel burnt for NO_x and below 1 g/kg for both CO and UHC. By extending the modelling to off-design conditions and embedding it within a broader supersonic aircraft conceptual design and mission analysis framework, the proposed eco-design model can support trajectory optimisation, inform future emissions-related regulatory standards, and contribute to the development and certification of next-generation sustainable high-speed aircraft.

HYDRA: A hydrogen capability demonstrator with modular exchangeable powertrain configurations

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1. Introduction / Objectives

The path to climate neutrality represents a major challenge for the aviation industry. In order to achieve the goals set in Flight Path 2050 for the next generation of commercial aircraft, innovative technologies must be developed, and old concepts redesigned from the ground up. In this context, new technologies and new energy sources that have already been developed on the ground must be tested under real flight conditions. This requires specially developed experimental aircraft that provide insights for the further development of new technologies and for future certification criteria. The goal is to design a demonstrator that can be used to investigate the potential of hydrogen propulsion systems, validate theoretical data, and test new technologies.

2. Methodology

To develop an innovative and fundamentally redesigned concept, a wide variety of implementation options are analyzed and compared using the morphological approach. The result of the morphological analysis is a common architecture for liquid hydrogen storage, batteries as a supporting energy source, and electric motors, implemented within the technology of Distributed Electric Propulsion, including a wingtip propeller as a wingtip device. The exchangeable components are Fuel Cells, and Turboshaft Engines with Generators. The modular concept is realized by using exchangeable containers housing the powertrain, enabling rapid powertrain replacement and reconfiguration. This enables flight test missions near the flight envelope boundaries, examining the performance of the powertrain and especially the thermal management system. An exemplary flight test near the stall speed for each configuration is further described. Additionally, further requirements of the hybrid-electric powertrain regarding operations are elaborated.

3. Results / Conclusions

The result is a feasible concept for a hydrogen demonstrator that, through modular interfaces, enables the testing of different liquid hydrogen powertrains. The design serves as the basis for further detailed construction of the demonstrator as well as further research into new technologies for the commercial aircraft of the future.
With this concept, Team HYDRA won this year's 10th Design Challenge organized by the German Aerospace Center (DLR). The Design Challenge is a national aircraft design competition in which teams from universities across Germany compete based on a common design task. In 2026, 16 teams from 10 universities submitted their designs.



Figure 1. *The HYDRA demonstrator concept.*

Laminar-Turbulent-Supercritical-Wing Concept and Its Aerodynamic Properties in Transonic Flight

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1. Introduction / Objectives

A Natural-Laminar-Flow (NLF) supercritical wing technology probably could bring us to a really green aviation. However, this technology is risky, especially within the domain of large passenger aircraft. This is because the NLF wing, compared to the purely turbulent one, is usually more likely to experience a low-speed-high-angle-of-attack deep stall as well as transonic buffet onset. To avoid the above disadvantages, an innovative Laminar-Turbulent-Supercritical (LTS) wing concept was developed. The idea assumes that the supercritical wing, designed in NLF technology, behaves as a purely turbulent wing in flight conditions where laminar flow on the wing surface threatens flight safety. This is achieved by forcing the laminar-turbulent transition on the wing surface, but only when needed. The work aimed to develop innovative technology that enables effective control of flow (laminar vs turbulent) on the wing and to verify this technology using computer simulations.

2. Methodology

Computational studies of the LTS wing equipped with RMV were conducted for a simplified wing segment. The study focused on two wing configurations shown on the left and right sides of Figure 1, respectively. The first configuration is a supercritical NLF wing, and the second is the same wing equipped with RMV (Retractable Micro Vanes). In the latter case, under nominal transonic flight conditions, the RMV are retracted inside the wing. When wing loads increase dramatically (e.g., due to a sudden vertical gust), the RMV are quickly extended outboard and begin to act as boundary layer trips. The wing then acquires the

characteristics of a turbulent wing.
Presented CFD simulations were conducted for 6 rows of RMV of height 0.125% of the wing chord, located at 20% of the wing chord. The Unsteady Reynolds-Averaged Navier-Stokes Equations (URANS) describing flow around the wing were solved using the ANSYS FLUENT solver. The airflow model was unsteady, 3D, compressible, and viscous. The four-equation "Transition SST" turbulence model was applied. The effect of gradually extending the micro-vane from the wing inside was simulated by gradually changing the boundary-condition type (from "interior" to "wall") of the cell walls corresponding to the given vane. A simple Closed-Loop Control (CLC) of the transonic buffet was introduced. The control system was based on the correlation between a current wing load and the probability of transonic buffet onset. Namely, the assumption was made that during flight, the RMV would be activated (moved outwards from the wing, perpendicular to its surface) when the increasing load factor n = L /W exceeded the threshold of 1.3 (where L is the lift force and W is the aircraft weight). The CFD simulations were conducted for the following flight conditions: M=0.7, Re=$2.67 \cdot 10^6$, C_L=0.76 and for two wing configurations: the clean NLF wing and the LTS wing equipped with RMV. For the later configuration, when the load factor n exceeded the threshold 1.3, the RMV were activated i.e. they were quickly moved outside the wing, which in fact changed the flow character on the wing, from laminar to turbulent.

3. Results / Conclusions

Results of flight simulations, shown in Figure 2, present the dependencies of the lift coefficient (CL) vs. time (t). For the NLF wing, the transonic buffet is well visible, as high-amplitude oscillations of the lift coefficient. These oscillations were not observed in the case of the LTS wing.
Conducted CFD simulations showed that effective transonic-buffet control may be ensured by RMV of height at least 0.125% of the wing chord, preferably placed at 20% of the wing chord. In the considered flight conditions in the presence of a sudden vertical gust, in contrast to the clean NLF wing, for the LTS wing equipped with RMV, no transonic buffet onset was observed. In turn, in typical cruise flight conditions (no gust), the laminar properties of the LTS wing can give up to a 7% reduction in total drag compared to a purely turbulent wing.

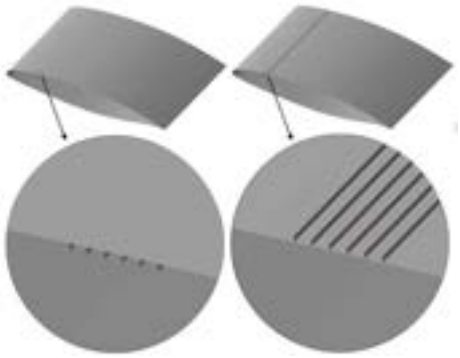


Figure 1. *The investigated model of a supersonic NLF wing equipped with an array of RMV. Left side: Clean NLF Wing with retracted RMV. Right side: LTS Wing with fully deployed RMV.*

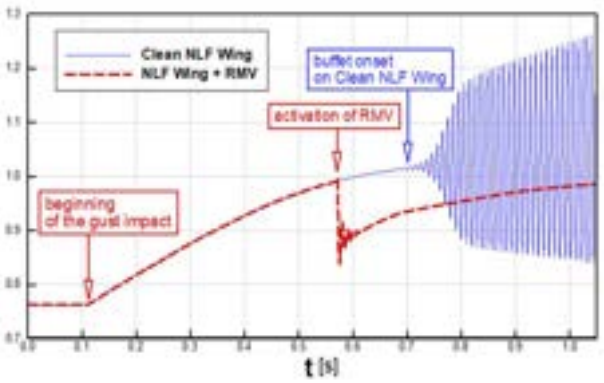


Figure 2. *Time history of transonic flight in sudden gust conditions for two compared configurations: "Clean NLF Wing" (natural laminar flow) and "NLF WING + RMV" (LTS wing equipped with RMV). Dependencies of lift coefficient (C_L) versus time (t).*

Airfoil Optimization for conceptual design of novel aircraft concepts

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With the goal to reach zero emissions in 2050, new and unconventional aircraft concepts, like the blended wing body and technologies like laminar flow control and variable camber are becoming integral research topics in conceptual aircraft design. The aerodynamic performance is a key aspect in design and evaluation of novel aircraft concepts, and the established semi-empirical calculation methods pose a growing limitation for accurate predictions of these concepts. For this reason, the conceptual aircraft design must transition towards higher fidelity aerodynamic calculation methos, for which the aerodynamic optimization of the airfoils is one important step.
This paper presents the methodology of a 2D airfoil optimizer developed at the Institute of Aerospace Systems (ILR), and the necessary adaptions to the relevant use cases.
Before developing an optimization process, the use cases must be specified. Current research topics at the ILR, which can benefit from tailored airfoils are the blended wing body (BWB) configuration, Hybrid Laminar Flow Technology (HLFC) and variable camber (VC). Each of these three use cases have specific constraints and additional parameters for optimization. For the BWB, conventional supercritical airfoils are needed in the outer wing, whereas the centerbody needs large chord lengths and special consideration towards cabin integration and pitching moment. For HLFC, the transition of upper side air flow from laminar to turbulent can be influenced by boundary layer ingestion through a specific suction distribution. For VC, a multi-point optimization is needed, to ensure good aerodynamic performance not only for the clean airfoil but also for deflected control surfaces.
As a suitable flow solver, SU2 is chosen. The flow field is calculated via the Reynolds Averaged Navier Stokes Equations (RANS). For modelling of laminar flow, the transitions prediction tool STABTOOL is used, which calculates the transition location on the airfoil surface via the linear stability theory. With this setup, it is possible, to model both transonic and transition effects according to the use cases, as shown in figure 1.
Regarding the airfoil parametrization, the Class Shape Refinement Transformation (CSRT) is used, which parametrizes an airfoil via Bernstein polynomials and can impose locally restricted variations in the airfoil shape.
For the optimization process, Bayesian Optimization (BO) is used. BO is suitable for the exploration of the design space identifying a global optimum, as well as refining a found global optimum. Using a comparatively small sample size, a balance between known function values defining a mean function and model uncertainty characterizes the strategy of exploration and exploitation.

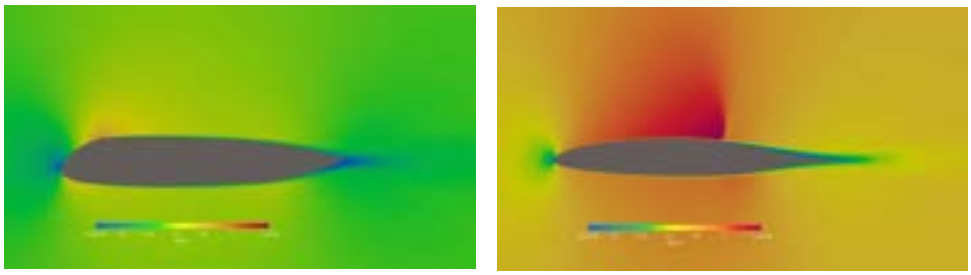


Figure 1. *Exemplary CFD calculations for a BWB fuselage airfoil (left) and a high speed laminar airfoil (right)*

Optimized 2D airfoils are a valuable foundation for the conceptual aerodynamic design. They can be used either directly in the design process via quasi 3D methods or as a baseline for further CFD based 3D shape optimization. With the developed optimizer, it is possible to optimize airfoils tailored to specific aircraft configurations and use cases. For the BWB it is possible to design transonic airfoils for maximised aerodynamic performance and centerbody airfoils to achieve natural trim stability for the design condition. Based on the CFD based optimization, it is possible to assess the aerodynamic benefits of HLFC and VC compared to a conventional wing and to feed these results into an overall aircraft design process to determine the emissions savings potential.

An Ice-Tolerant Tailplane Sizing Methodology for High-Aspect-Ratio Truss-Braced Wings

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[2] Università degli Studi di Napoli Federico II, Italy
[3] German Aerospace Center (DLR), Germany

1. Introduction / Objectives

Next-generation commercial aircraft concepts, such as Truss-Braced Wing (TBW) configurations, promise significant aerodynamic efficiency gains but introduce novel design challenges not adequately explored by existing sizing methodologies. Among these, horizontal tailplane sizing under icing conditions represents a critical yet underexplored area. In-flight icing is one of the major causes of flight accidents posing substantial risks to aviation safety . While ice protection systems are commonly installed on main wings, their application to tailplanes is generally avoided due to penalties in weight, complexity, and cost. Nevertheless, CS-25 Section 25.143 requires aircraft controllability under critical ice accretion in all flight phases.
The objective of this study, performed within the **EXAELIA project** , is the development of a low computational cost framework for tailplane sizing that integrates ice-induced aerodynamic degradation into longitudinal stability and control assessments. The main innovation lies in the integration of ice-aware design into early-stage sizing of non-conventional TBW aircraft.

2. Methodology

The proposed methodology establishes longitudinal stability and control constraints that define the feasible horizontal tail sizing space across a user-specified center-of-gravity (CoG) range. Three constraints are considered:

1. Longitudinal static stability;
2. Landing trim;
3. Takeoff rotation capability.

Each constraint yields an independent relationship between the tail-to-wing area ratio S_H/S_w and CoG position; the final sizing envelope is defined as the maximum of these curves. Icing

effects are incorporated from a critical reference scenario through aerodynamic coefficient degradation factors that consider modification in lift curve:

- $K_{Cl\alpha} = C_{l\alpha,\text{iced}}/C_{l\alpha,\text{clean}}$
- $K_{\text{Clmax}} = C_{l\text{max,iced}}/C_{l\text{max,clean}}$

These factors are encoded in response surfaces constructed over structured datasets. Two-dimensional ice accretion analyses are conducted to identify the most critical atmospheric conditions — specifically, the combinations of variables that produce the greatest aerodynamic degradation. Extrapolation to 3D geometries is achieved via a 2.5D approach that accounts for wing planform shape. The resulting corrective factors are subsequently integrated into the sizing methodology. This approach has demonstrated satisfactory agreement with high-fidelity 3D icing simulations in prior work.

For each design point within the TBW configuration space, corrective factors are retrieved through response surface interpolation, and the three longitudinal constraints are re-evaluated under degraded aerodynamic conditions. This modifies the S_H/S_w versus CoG curves, quantifying the increment of tail surface necessitated by accounting for icing related aerodynamic degradation. The framework is implemented as a modular computational tool, supporting parametric studies across the TBW design space.

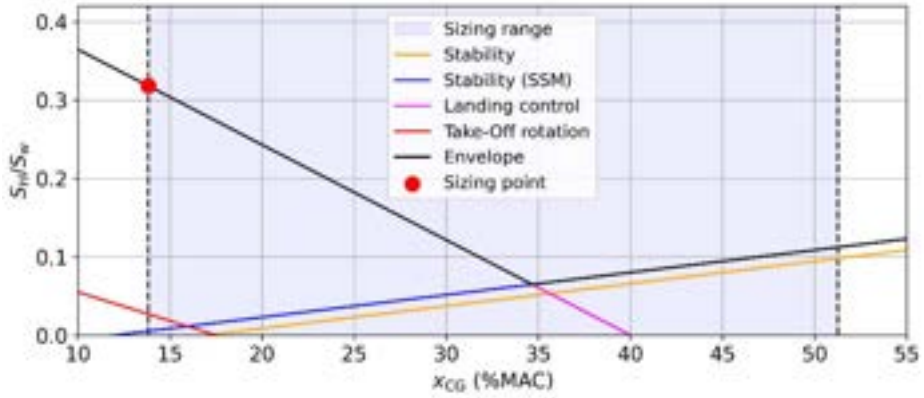


Figure 1. *An example of application of the methodology. SSM =5%MAC, max forward CoG = 13.83%MAC, max aft CoG = 51.3% MAC.*

3. Results / Conclusions

The proposed framework enables rapid horizontal tailplane sizing for Truss-Braced Wing configurations under icing conditions, reducing computational cost from the weeks required for full 3D assessments to seconds, while maintaining satisfactory accuracy. An illustrative application reported in Figure 1 yields a tail-to-wing area ratio of 0.318 to satisfy all longitudinal constraints.

The modular architecture ensures full compatibility with conceptual design workflows and straightforward integration into MDO environments, requiring no high-fidelity CFD at the sizing stage. By embedding ice-aware aerodynamic degradation from the earliest design phases, the methodology supports more robust and safety-compliant aircraft concepts. This is particularly relevant for novel configurations such as TBW aircraft, where conventional sizing practices remain unverified due to the lack of prior application, and where early

identification of icing-driven design drivers can meaningfully influence configuration trade studies.

Acknowledgement: Funded by the European Union (Project 101191922 – EXAELIA). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

The roadmap for sustainable aviation regarding noise reduction: main objectives, solutions and key considerations

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1. Objectives

The path towards sustainable aviation requires a multi-pronged approach. As well as emissions, noise is another key issue. The European Environment Agency (EEA) reports that over 3 million people in Europe are regularly exposed to harmful noise levels from aviation . Many of these exceed the 55 dB Lden threshold recommended by the World Health Organization (WHO) . This study provides a comprehensive overview of the key factors to consider when assessing aviation noise reduction. It identifies the main industry trends and defines a roadmap for progressing towards noise reduction in aviation. The main contributions are organised in relation to three topics:

- Current regulatory framework regarding noise.
- Technological and operational solutions that can contribute to noise reduction.
- A general roadmap for a quieter aviation sector.

The study aims to provide a practical overview of the current regulatory framework and potential solutions, along with a roadmap for their effective implementation in aviation.

2. Methodology

To address the key aspects of noise reduction in aviation, this study follows a research-oriented approach.
The study is part of the European project Environmentally Friendly Aviation for All Classes of Aircraft (EFACA). One of the project's objectives is to develop a holistic analysis of sustainable aviation by proposing different types of propulsion for each aircraft class. This holistic approach is applied in this study.
The first step is to present a comprehensive overview of the main noise-related regulations governing the aviation industry. This is particularly relevant considering the new approaches set out in ICAO's Committee on Aviation Environmental Protection (CAEP) last cycle of work, CAEP/13.
Next, solutions for achieving noise reduction are analysed. To develop this part of the study, many recent scientific publications and industrial contributions were reviewed. Regarding technological measures, the analysis focuses on specific aircraft components, including

engines and propulsion systems, as well as wings and aerodynamics. The importance of considering community perception when implementing measures is also considered.

Finally, after analysing the current regulatory framework and the proposed measures, the study concludes by defining a roadmap. The methodology is organised into two stages. Firstly, five strategic objectives are defined to reduce aviation noise. These are: i) promoting new technologies, ii) modernising noise assessment methods, iii) integrating noise optimisation into air traffic management, iv) establishing synergies between communities and airports, and v) applying incentives.
Secondly, the methodology sets out an action and implementation plan organised into three stages beginning in 2026 and running until 2050, with the aim of making progress towards the aforementioned objectives. Phase I, which is proposed to run from 2026 to 2030, aims to establish technological foundations and develop validation tests. Phase 2 runs from 2030 to 2040, focusing on deployment and integration at airport level. The third and final phase will focus on assessing the large-scale impact and fostering harmony with local communities. Specific objectives and key actions to be carried out are proposed for each stage.

3. Results

Considering the three objectives described above, this work's three main contributions are as follows:

1) A proposal for a set of certification requirements for future aircraft, considering the current regulatory framework.

2) A presentation and analysis of the portfolio of technical and operational measures for reducing aviation noise.

3) A detailed explanation of the roadmap for the reduction of the acoustic impact of air transport in Europe, including the main stages, actions, and milestones. Figure 1 provides an overview of the three phases and some of the key actions considered by the proposed roadmap.

This work aims to present trends and define key actions for stakeholders in the aviation sector to consider moving towards quieter aviation.

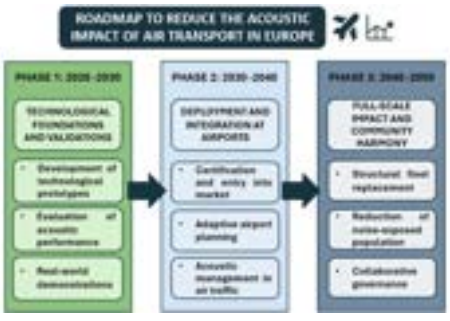


Figure 1. *Key phases considered in the roadmap for the reduction of the acoustic impact of air transport in Europe*

A Mid-Fidelity Aeroacoustic Assessment of the Hydrogen-Fuel-Cell Propulsion System Ground Demonstrator of the NEWBORN Project

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1. Introduction

Hydrogen fuel-cell and battery-electric technologies are key enablers for reducing the climate impact of short-range air transport while preserving the operational flexibility required by commuter and regional aircraft. In this framework, the EU-funded NEWBORN project targets the maturation of a megawatt-class hydrogen fuel-cell propulsion system for future CS-23 and regional aircraft applications. Beyond emissions, the introduction of fuel-cell powertrains modifies the aircraft aero-vibro-acoustic environment: propeller tonal noise remains a dominant contributor, while compressors, fuel-cell balance-of-plant components, air-recirculation units and thermal-management systems may introduce additional tonal and broadband sources. The present work develops and applies a medium-fidelity aerodynamic/aeroacoustic methodology to the NEWBORN ground demonstrator, focusing on propeller-generated noise, ground and installation effects for the extrapolation of demonstrator data toward free-field and flight- conditions.

2. Methodology

The assessment is based on CIRA's coupled aerodynamic–acoustic workflow, conceived to provide medium-fidelity propeller-noise predictions with affordable computational resources and to support the interpretation of ground-test results. The reference case is the NEWBORN full ground demonstrator equipped with a seven-bladed propeller. Both isolated free-field conditions and ground-demonstrator configurations including ground-effect and installation effects are analysed.

The aerodynamic database is generated with RAMSYS, CIRA's unsteady, inviscid and incompressible free-wake panel solver for rotary-wing and multi-body interactional aerodynamics. The method solves the potential-flow problem through a boundary-integral formulation and explicitly convects the wake, thus providing the unsteady blade loading and surface pressure distributions required by the acoustic solver. The use of a free-wake formulation is particularly relevant for the present static configuration, where wake contraction, tip-vortex convection and interactions with the ground and support environment directly affect the unsteady loading harmonics.

Far-field propeller noise is predicted with ACO-FWH, using the unsteady pressure database as input. The solver implements the Ffowcs Williams–Hawkings acoustic analogy in an advanced-time formulation; thickness and loading noise contributions are integrated over the moving impermeable blade surfaces. The installed acoustic field, including scattering and radiation effects induced by the demonstrator layout and ground plane, is then addressed with ACO-FAM, an acoustic boundary-element solver accelerated through an adaptive black-box fast multipole method. This step enables the separation of source-generation effects from propagation and installation effects and supports the extrapolation of ground-test results toward isolated-propeller free-field conditions, aircraft-fuselage installation effects and flight-relevant conditions.

3. Results

Preliminary aerodynamic simulations reproduce the slipstream acceleration, wake contraction and convection of the seven-bladed propeller tip-vortex system under static ground-demonstrator conditions. The interaction between the propeller wake and the demonstrator generates a significant wake roll-up. The flow field was further analysed on three selected planes, while velocity time histories were extracted at nine monitoring points distributed over the ground-demonstrator configuration. The resulting unsteady blade-loading database provides the input for the FW-H acoustic prediction and for the subsequent BEM/FMM installation analysis. This workflow enables a consistent link between aerodynamic loading, propeller-noise generation and ground/installation scattering, establishing a validation-oriented aeroacoustic framework. The final contribution will report the installed acoustic field, compare free-field and installed configurations, and the results of the extrapolation procedure from ground-demonstrator to propeller free-field conditions, aircraft-fuselage installation effects and flight-relevant conditions. Thus, the expected impact is the establishment of a validated and computationally efficient methodology for assessing aeroacoustic installation effects in hydrogen fuel-cell propeller-driven aircraft.

Acknowledgment: This research was funded by the European Union's Horizon Europe research and innovation programme under grant agreement No. 101101967, project NEWBORN — NExt generation high poWer fuel cells for airBORNe applications.

Uncertainty-aware global sensitivity analysis for aircraft conceptual design

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1. Introduction / Objectives

During the conceptual design phase of a novel aircraft, the preliminary assessment of key performance metrics, including aircraft weight, fuel consumption, and emissions, is inherently affected by uncertainties. These uncertainties are of two distinct types Epistemic uncertainty arises from a lack of knowledge in a specific design context and is in principle reducible as knowledge improves. Aleatory uncertainty, by contrast, is irreducible and stems from the inherent variability of operative mission conditions. Understanding which uncertain inputs contribute most to the total output uncertainty is essential for informed design decisions and prioritising modelling effort. This manuscript proposes an efficient methodology to quantify the impact of the aleatory (mission related) uncertain inputs on total output uncertainty, applying methods for the global sensitivity analysis (GSA)to the aircraft conceptual design framework and reducing their computation cost by using surrogate models to expand the available design dataset. The ATR72 is chosen as the reference model for this application.

2. Methodology

Performing GSA via Sobol indices requires $(2d + 2) \times n$ model evaluation, where n is the sample size per matrix row, (typically n> 10^3), and d is the dimension of the uncertain input vector $\mathbf{X} = (X_1, X_2, \dots, X_d)$. Given the high computational cost of each physics-based simulation, direct methods such as Monte Carlo Simulation are not practically viable at

conceptual design stage. A surrogate model would be suited to reduce the computational cost.

However, the adoption of a surrogate model inherently introduces an additional source of uncertainty due to the model uncertainty itself. It is therefore mandatory to use an uncertainty-aware surrogate model, namely a Bayesian Neural Network (BNN). To identify the most suitable inference algorithm, three approaches are evaluated: Monte Carlo Dropout (MCD), Bayes by Backprop (BBB), and Black-Box Alpha divergence (BB-α). Each algorithm is assessed in terms of epistemic uncertainty estimation and predictive accuracy by querying the trained BNN with the validation dataset and comparing the resulting mean and standard deviation against the physical reference model.
Results from the physical system show that, although the input vector is constrained within the Operational Design Domain (ODD), certain combinations lead to physically infeasible operating points. This behavior is attributed to the physical constraints of the system, namely the available engine power. Therefore, a boundary condition is set based on the maximum operative altitude $h_{SC}(M, \Delta T, ZFM, Range)$ constrains the admissible combinations of the relevant input variables, where M represents the Mach number, ΔT the ISA temperature deviation and ZFM the zero-fuel mass.
A query violating $h \leq h_{SC}$ would simply be extrapolated from the BNN and assessed the GSA. To prevent this, after the BNN is prompted to derive the block fuel for the specific mission, the non-physical results are excluded from the sampling data for the GSA This renders the GSA physics-aware through explicit physical knowledge enforced at inference time. The probabilistic nature of the BNN then enables decomposition of the Sobol indices across the predictive mean μ^-, the aleatoric variance σ_{al}^2, and the epistemic variance σ_{ep}^2, identifying which inputs drive the mean output response, which govern irreducible physical variability, and where additional simulation data would most effectively reduce model uncertainty.

3. Results / Conclusions

Results show that the BNN, trained with 1800 samples, accurately captures the mean and standard deviation of the physical system outputs. MC Dropout outperformed the other methods in both predictive accuracy and epistemic uncertainty estimation, with MAPE below 5% for five of the six output variables.
The GSA reveals qualitatively different sensitivity structures across the three quantities of interest. The mean is dominated by Range (first-order index ≈ 93%), with altitude contributing a secondary 6.5%. Both aleatory and epistemic uncertainty, by contrast, are governed by interaction effects. Altitude has a near-zero first-order index but a total-effect index of 18–23%, followed by Mach number and rates of climb and descent (4–6% each). While the aleatory structure is irreducible, the epistemic pattern identifies high-altitude, short-range, high-Mach combinations as data-sparse regions where targeted additional simulations would most efficiently reduce model uncertainty.

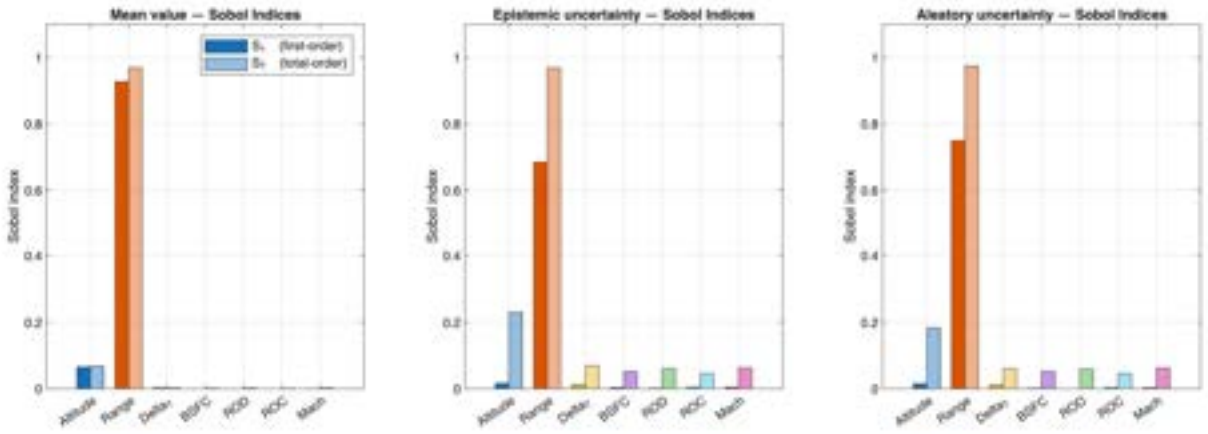


Figure 1 Sobol analysis for block fuel

Multidisciplinary Design Optimization of Hybrid Aircraft : Influence of the Range of Mission Profiles on Optimal Design

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Introduction / Objectives

In 2021, the IATA announced a plan to achieve net zero emissions by 2050. Electrification is a potential solution, but battery energy density limits its feasibility for medium- and long-haul flights, directing research efforts toward regional aviation. To support these investigations, ONERA and ISAE-Supaero developed FAST-OAD a preliminary aircraft design tool which will be used on this article. Between 2018 and 2021, the HASTECS project focused on optimizing hybrid-electric propulsion by developing parametric technological models of key components and integrating them into a complete powertrain system. This approach accounted for electrical, mechanical, and thermal phenomena, including cooling mechanisms and high-voltage effects. The last study presented in, presents the new Multidisciplinary Design Analysis (MDA) which combines the regional aircraft model developed during Palladino thesis based on FAST-OAD tools with the HASTECS powertrain models. Alongside the MDA, a Multidisciplinary Design Optimization (MDO) is presented to determine the optimal architecture and component sizing for a hybrid-electric regional aircraft based on the evaluation of the fuel consumption during the design mission. Although the optimization yields only a few percent of fuel reduction on the design mission, hybrid-electric aircraft can exhibit more substantial fuel benefits on shorter missions, since the same amount of battery energy is carried regardless of mission length. Also, as explained by Ty V. Marien *et all*, the majority of the turboprop aircraft flights are less than 500 nautical miles even though the ATR72 is designed for 750 nautical miles. That the reason why, in this article,

another optimization is performed to explore the variation of the optimal solution regarding a range of mission profiles instead of a single one.

2. Methodology

In the article, the authors determine the fuel consumption for different payload and range, and conclude in different best solution when the typical mission is observed compare to the fuel consumption for the design mission. This result shows the importance for hybrid regional aircraft to optimize an aircraft for shorter missions than the design mission. The authors also provided diagrams relating fuel consumption to payload and range, thereby illustrating the strong dependence of achievable fuel savings on the selected mission profile. To construct such comprehensive diagrams requires either simulating a wide set of mission scenarios or employing simplified analytical models such as the Breguet equation. On the other hand, once the fuel efficiency as a function of range and payload is known, it is possible to estimate the global fuel consumption of the regional air transportation using recorded flight data. The global fuel consumption can then be used as an objective function in the optimization of the hybrid electric aircraft. This removes the need to select a specific mission for optimization and ensures the maximum fuel economy over the actual usage of the aircraft.

To be able to perform optimization using the global fuel consumption as the objective function, one needs to limit the computational cost of mission simulation. The first option is to use a Breguet formulation instead of a time varying mission simulation. However, in the case of regional aircraft, climb and descent phases account for a significative share of the total fuel consumption, which makes the use of Breguet Equation irrelevant. Simulating all the missions flown would be too computationally expensive. Therefore, another solution is to determine a weighted set of representative mission profiles, based on the distribution of recorded flights and to simulate only this reduced set of missions.

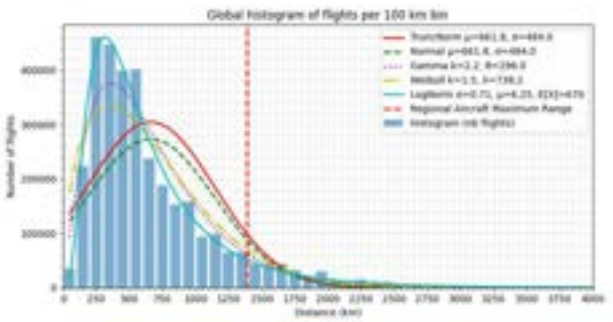


Figure 27: Flight number in function of the flight range for aircraft between 70 and 90 passengers extracted from the OAG 2018 database

To determine the ponderation of each mission profile, all the mission profiles for aircraft with seat number between 70 and 90 on the Official Airline Guide (OAG) 2018 database are extracted. As shown in figure 1, the mission profiles are nearby to a LogNormal distribution with an expected value of 670 km.

The global fuel consumption can be reasonably well approximated by the weighted sum of the fuel consumption for each mission profile using the distribution parameters obtain on the figure. The weight represents the occurrence of the mission in the flight database which will be multiply by the fuel consumption of his mission range. This new formulation introduces a

parameter to compare the fuel burn of the existing regional fleet with a fleet of the MDO results hybrid aircraft.

3. Results / Conclusions

The optimization with the set of missions will show the different optimal solutions in term of hybridization and topology of the aircraft than the MDO with the fuel consumption of the design mission as the objective function. It will also illustrate how hybrid aircraft can be cleverly designed to reduce fuel consumptions on short distances while limiting the penalty for missions of longer range This new objective function presents a better vision of the possible benefits of hybrid regional aircraft which are not the case for the design mission fuel burn due to the low occurrence of the design mission and the constant onboard battery energy.

Quantifying Sensitivities and Efficiency Penalties of Conventional TLARs on Fuel-Cell-Electric Regional Architectures

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1. Introduction / Objectives

Within ACARE's (Advisory Council for Aviation Research and Innovation in Europe) updated roadmap "Flying the Green Deal", Europe is defining its pathway of sustainable aviation. It is stated that fuel cells and the resulting electric propulsion architecture are among the promising technologies to be introduced in the mid- to long-term future. While integration on short-and-medium range aircraft remains constrained in the next decade, technology maturation typically initiates within lower-complexity applications. Regional aircraft, owing to their operational envelopes and certification trajectories, function as optimal testbeds for technology scale-up and empirical data acquisition, thereby informing subsequent larger-scale system integration. To accelerate the progression towards technology integration, an understanding of design drivers and differences between conventional and novel propulsion systems is crucial. In that sense, this study investigates the correlation between top-level aircraft requirements (TLARs) and fuel cell sizing points to mitigate technology-induced constraints and sensitivities in the conceptual aircraft design.

2. Methodology

In accordance to the established convention of a project, the TLARs are designated as the reference point for the aircraft design. Especially performance requirements such as the initial cruise altitude and cruise Mach number are derived from comparable and existing aircraft or market interests and are often not aligned with alternative propulsion technologies and the optimal operating conditions of the subsystems. The consequence of this is an increase in power requirements, which can result in discrepancies between the technology assumptions for the entry-into-service (EIS) of the components and an aircraft design that is not operating in its most efficient environment. Previous research demonstrated that shifting the design cruise point to conditions maximizing electrochemical efficiency yields to substantial overall aircraft efficiency improvements through coupled aerodynamic and

propulsion optimizations. The analysis utilizes a regional aircraft configuration developed within the German-funded project ZEBRA (Zero Emission Baseline and Refined Architecture). The project focusses on a high-wing propeller design (100 passengers, 1000 NM design range, EIS 2035) powered by numerous proton exchange membrane fuel cells (PEMFC), which are integrated in underwing nacelles. The configuration is depicted in Figure. Multi-disciplinary evaluations are conducted within the RCE framework, coupling low- and higher-fidelity computational tools across aerodynamic, propulsion, and mission-analysis disciplines. Building upon the prior design space explorations of the performance parameters (cruise Mach number & initial cruise altitude), this study implements a refined powerplant sizing methodology to quantify the influence of the take-off field length requirement on aircraft block fuel consumption. The detailed take-off analysis subsequently enables trade-offs between the wing loading, the required take-off power and cruise performance in each design point. The PEMFC system design is iteratively optimized to determine the optimum oversizing factor, balancing stack efficiency at design power loading with the system requirements and overall system weight reduction. In addition, the same trade-offs are performed using a conventional turboprop reference model (Figure) to investigate the sensitivities and differing correlations in conventional applications.



Figure1: Fuel-Cell Powered Aircraft Baseline Concept (left) vs Conventional, SAF-powered Reference Configuration (right)

3. Results / Conclusions

This study demonstrates that conventional TLARs, while effective for legacy propulsion, impose significant efficiency penalties on fuel-cell-electric architectures due to misaligned operational envelopes as previous work identified a cruise fuel consumption advantage of up to 13%. As a result of the optimization of take-off performance, the total required shaft power is estimated to be even lower compared to the baseline aircraft. Optimizing the design process right from the beginning leads to block energy advantages compared to current design points due to an enhanced aerodynamic efficiency and improved fuel cell system performance.

Furthermore, within this paper it will be shown that fuel-cell-electric architectures exhibit increased sensitivity to TLAR variations relative to traditional propulsive systems, underscoring the necessity for technology-aware constraint definition. Integrating propulsion-specific

operational envelopes early in conceptual design is essential to mitigate power penalties, optimize system integration, and accelerate the viability of zero-emission regional aviation.

Acknowledgement: The work was supported by the Federal Ministry for Economic Affairs and Climate Action as per resolution of the German Bundestag under grant number 20M2240B and is performed within the framework of the ZEBRA project (Zero Emission Baseline and Refined Architectures).

Assessing Noise-Related Environmental Interdependencies of EFACA Aircraft Technologies across Vehicle, Airport and Fleet Levels

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1. Introduction

The Green Aviation Transition offers various opportunities for aviation sector - reduction of greenhouse emissions and fossil fuel consumption, improvement of LAQ in the airport vicinity, enhancement of airport and aviation industry resilience etc in accordance with ACARE 2035 ad 2050 goals. In addition, recent studies suggest that stakeholders should consider new criteria for aircraft selection to ensure sustainable development, and now they include emission and noise characteristics - in addition to fuel, performance and economic parameters. However, growing evidence indicates that novel hydrogen-powered and hybrid-electric aircraft may involve important environmental trade-offs: reductions in CO_2 and LAQ emissions can be accompanied by increased noise contour areas. This highlights the need for an integrated framework that jointly assesses noise, emissions and fleet-transition effects. The EFACA project proposes two central aircraft concepts: for regional (a propeller 80-PAX RA with two hybrid turbo-electric power propulsion consisting of a gas turbine engine and an electric engine, which is powered by hydrogen fuel cells (fig. 1.a). and short- and medium range (150-seat LH2-fueled aircraft) aircraft classes – both flying along the quite short distances till 1000 miles. Although both aircraft categories are not dominant contributors to the overall aviation GHG and LAQ emissions inventory, their current concepts provide a relevant basis for mid-term assessment of noise-related trade-offs and their potential implications for integrated airport-level environmental performance.ir efficiency.



a) ***b)***

Figure 1. *Layout of the EFACA aircraft: a) HEP aircraft; b) LH_2-fueled SMR aircraft [2,3]*

2. Methodology

To assess the environmental impact of novel types of hydrogen aviation and mitigate power of noise and emission interdependencies the multi-scale, bottom-up methodological approach was proposed, combining fleet-level trade-off analysis at both airport and global levels. The methodology is based on the integration of aircraft-level performance results, including fuel consumption, emissions, and noise criteria, which are upscaled to represent fleet operations over time. Within the EFACA project framework, these approaches are integrated into a single space for environmental modeling – VALDES (the **V**ehicle-**A**irport-f**L**eet-**DES**ign) platform – similar to the FAA AEDT or EUROCONTROL IMPACT programs, adapted to hybrid-electric and LH_2 configurations, which cannot be completely described by standard data sets for conventional aircraft.

On the **vehicle level**, a single set of input parameters is formed for noise, emission and energy modeling: flight path, height, operational performance, mode, configuration flight, parameters of the power plant, fuel consumption, and the stage of hybridization. The vehicle level provides the baseline for identification of trade-offs among key environmental factors and creates feedback mechanism for manufacturers. The results of the integrated assessment is used to adjust design decisions to achieve a higher level of environmental excellence.

At **the airport level** the EFACAport concept is implemented as environment for scenario-based analysis of environmental efficiency tradeoffs, as well as operational interactions between noise, LAQ, CO_2, non-CO_2 effects.

To clarify airport scenarios, the FRIDA (**F**light **R**adar data for **I**nter**D**ependency **A**nalysis, Python toolkit) approach is used, focusing on processing ADS-B/FR24 data and further updating of aircraft operational VALDES profiles from real or reconstructed trajectories and refine them airport-level interdependencies for noise and emission modeling.

At **the fleet-level**, the results of the vehicle-level and airport-level assessment are aggregated for a scenario analysis of the current structure of the fleet of aircraft. The shares of the of HEP, LH_2 vs reference kerosene types in the fleet structure are considered as scenario strategies that indicate the total inflow to the fleet for noise, CO_2, non-CO_2 effects, local air quality, energy consumption and throughput the flexibility of the airport system.

3. Results & Conclusions

The study proposes the results of scenario-based analysis for assessing environmental interdependencies using EFACA technology on a vehicle, airport and fleet levels. Scenarios focus on cases where changes in CO_2, non-CO_2 and LAQ-related emissions could be accompanied by potential increases in noise pollution around airports. The main result is the importance of mechanisms for reducing such mutual relationships at the appropriate level: clarification of the operational profiles at the vehicle level, adaptation of operating procedures at the EFACAport, as well as analysis fleet structure scenarios that will accommodate HEP, LH_2 and conventional kerosene aircraft types, and the designated reach of ACARE's mid- and long-term environmental targets within a single VALDES-based assessment framework.

Fleet-Level Effectiveness and Fuel Penalty of Vertical Contrail Avoidance for Long-Range Aircraft in Conceptual Design

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1. Introduction / Objectives

Global air traffic volume is expected to grow at an average annual rate of 3.4% through 2050, further increasing the climate impact of commercial aviation. Beyond CO_2 emissions, persistent contrails (PCs) from the interaction of engine exhaust and ambient air contribute considerably to the aviation climate effects. Since PCs only form under specific atmospheric conditions, studies have shown that avoiding flying through persistent contrail regions (PCRs) can reduce PC formation significantly. However, deviating from the design cruise altitude increases fuel consumption for a given mission. This work assesses the fleet-level effectiveness and resulting fuel penalty of contrail avoidance maneuvers via altitude change for long-range aircraft. Furthermore, it evaluates the potential of selected airframe and engine technologies to enhance altitude flexibility.

2. Methodology

The methodology begins with the design of a baseline long-range aircraft using the preliminary aircraft design environment BLADE, assuming a technology level of EIS 2035. This includes a particle emission model to enhance the fidelity of subsequent contrail predictions. In parallel, 50 high-frequency routes are selected from 2018 global commercial flight data to represent the actual operational profile of long-range aircraft. To account for the high location-dependency of contrail formation, the selection model preserves the geographical and directional distribution of the global network. Since PCs primarily form at cruise altitude, only routes where cruise time exceeds 50% of the total mission duration are considered. These routes (Figure 1) define the horizontal trajectories for both the reference and adapted missions.

For the reference mission, the vertical trajectory is optimized for minimum block fuel consumption. Subsequently, PCRs along these routes are identified using CoCiP and 2019 meteorological data. CoCiP is a physics-based Lagrangian plume model that simulates the full contrail life cycle with meteorological and aircraft performance data. The vertical trajectories are then adjusted to avoid PCRs via altitude changes without lateral deviation, forming the adapted mission. By comparing these missions, the trade-offs between climate impact and the fleet-level fuel penalty from vertical contrail avoidance are quantified. Finally, this study evaluates potential design modifications, such as integrating variable camber wings or adjusting the wing loading and engine design point, to mitigate this penalty from operating at suboptimal altitudes.



Figure 1. *Selected representative routes for long-range aircraft utilization.*

3. Results / Conclusions

Preliminary analysis of the baseline aircraft shows that descending from a design cruise altitude of 35,000 ft to 29,000 ft reduces the lift-to-drag ratio by 2.8% due to a lower, suboptimal lift coefficient. When coupled with a shift in the engine operating point away from its design optimum due to higher ambient air density, the fuel flow during such an avoidance maneuver increases by 4.9%. While this introduces additional fuel burn and thus CO_2 emission, vertical contrail avoidance is still expected to yield a net climate benefit, in line with prior research. This underscores the necessity for next-gen aircraft to maintain high efficiency across a broader range of altitudes. To address this, this study quantifies the trade-offs between climate impact and off-design penalties at the fleet level and evaluates the potential of airframe and engine design modifications to improve aircraft altitude flexibility.

Impact Assessment in Aviation

Chaired by:
Dr. Jordi Pons Prats (Polytechnic University of Catalonia, Spain)

Ontology-Based Approach for Future Civil Aviation Technology Management to Combine Literature and Expert Knowledge

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1. Introduction / Objectives

The identification and assessment of technologies with potential benefits on aircraft level is crucial for defining pathways towards a more sustainable commercial air transport system. A holistic technology-foresight approach based on systematic technology management can highlight the most promising innovations and guide future research directions. Technology scouting is performed in various areas through expert interviews, workshops and resource-

intensive literature reviews. This work presents a technology scouting and management framework that integrates expert insights and literature-based findings into a semantically structured knowledge base. This addresses the question of how technology scouting can become more time-efficient through partly automating and enhancing the systematic structure of the process. By introducing a domain-specific technology ontology, the approach enables structured representation of technologies and their interdependencies. Interfaces to data entry points in form of a web-based expert contribution form and an automated literature scouting framework facilitate the seamless integration of technology knowledge from diverse sources.

2. Methodology

The development of a technology ontology builds on the technology scouting and integration approach described by Weber et. al and focuses on benefit identification and quantification, thereby enabling a standardized workflow for integrating prospective technologies into high-level aircraft designs. An additional new focus within the technology knowledge is a systematic description of inter-technology dependencies. The core-task is the definition of a detailed vocabulary for technology classification and relations build using Semantic Web Technologies such as RDF, RDFS and OWL.

A standardized reference management links each technology information to literature and project ontologies. This semantic approach also enables associating technology benefit values to reference aircrafts, engines and missions. An existing CSV-based technology management format is automatically transformed into an RDF representation and implemented into the in-house developed semantic database called the SemanticHub (initially planned as part of the Codex Framework), establishing a single source of truth. Interfaces for the automation of technology scouting approaches are developed, building up a holistic technology scouting and management framework [see Figure 1].

In order to enable autonomous expert contribution, a copy of the SemanticHub is published on an internal DLR web platform alongside a link to a standardized electronic technology contribution form. Experts can complete the form whenever technology knowledge has expanded. Focus within the form development is an efficient and user-friendly contribution process saving expert's limited time and erasing the need for time-consuming meeting alignments and iterative knowledge exchange. A Python tool translates the form responses directly into the ontology, ensuring rapid knowledge-graph updates. To complement internal expertise, an interface to a large-language-model (LLM) -based literature scouting module is prototyped; full automation of literature ingestion is planned for future work.

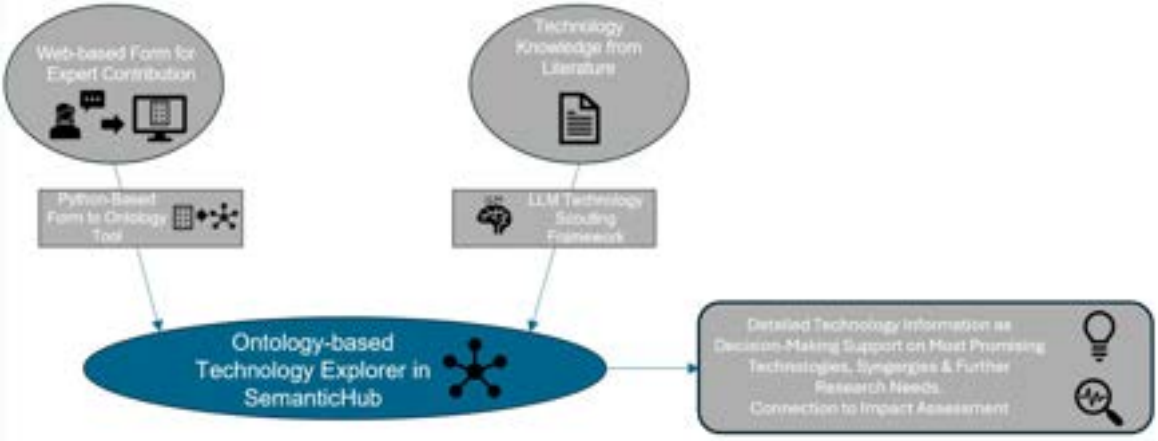


Figure 1. *Technology Scouting and Management Approach*

3. Results / Conclusions

The resulting technology ontology provides a detailed, cross-referencing vocabulary that makes interdependencies between technologies explicit and supports the connection of technology assessment and integration workflows. In contrast to manual technology management approaches using CSV files and ad-hoc aggregation of expert inputs and literature, this solution provides a pre-defined technology vocabulary and seamless, automated integration of multiple input sources, namely expert forms and literature data within a unified knowledge framework. The web-based contribution form and translation tool reduce the time required for expert input and enable state-of-the-art updates of the knowledge graph. Implementing literature information leveraging an LLM-based scouting interface will further improve technology scouting efficiency in the future. As a proof-of-concept, >100 pre-scouted technology records are implemented into the SemanticHub. A set of domain-specific SPARQL queries enables efficient, structured access to the knowledge graph for dynamic technology analysis and strategic decision support, demonstrating the framework's value for diverse stakeholders.

Architecting a System-of-Systems Framework for Impact Assessment in Aviation

Patrick Ratei, Prajwal Shiva Prakasha, Björn Nagel
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1. Introduction / Objectives

Aviation is essential for global connectivity, trade, and economic development, yet it contributes significantly to greenhouse gas emissions, non-CO_2 climate effects, and societal impacts such as noise exposure. Recent research increasingly recognizes aviation as a System of Systems (SoS), comprising interconnected stakeholders including airlines, airports, air traffic management, regulators, and passengers. A review of the literature reveals that existing impact assessment approaches largely focus on individual domains, such as

environmental performance, economic efficiency, or societal effects, with limited integration across these dimensions. Furthermore, current methodologies often fail to capture feedback loops, emergent behaviours, and cross-domain trade-offs that characterize complex aviation systems. To address these gaps, this paper proposes a multilevel SoS-based framework integrating environmental, economic, and societal metrics within a unified assessment approach. The framework aims to support more robust evaluation of aviation transformation strategies and enable informed decision-making for sustainable and competitive aviation futures.

2. Methodology

This research develops a System of Systems (SoS)-based framework for integrated aviation impact assessment, addressing the fragmented treatment of environmental, economic, and societal effects identified in the literature. Building on SoS principles, the framework captures interactions, feedback loops, and emergent behaviours across multiple aviation domains, enabling a more holistic evaluation of system transformations.

The framework consists of three interconnected layers. The environmental layer models greenhouse gas (GHG) and non-CO_2 emissions, including Sustainable Aviation Fuel (SAF) life-cycle impacts and contrail effects. The economic layer evaluates operational performance, cost-benefit trade-offs, and market dynamics associated with mitigation strategies. The societal layer assesses noise exposure, accessibility, and equity implications using geospatial and socio-economic indicators. Shared data streams and dynamic feedback mechanisms link these layers to represent cross-domain dependencies and emergent system behaviour.

To evaluate potential aviation transition pathways, a set of scenarios is developed covering mitigation measures such as SAF deployment, contrail avoidance strategies, and regulatory interventions. Scenario-based analyses incorporate feedback effects between environmental, economic, and societal outcomes to identify trade-offs and unintended consequences that may not be captured by conventional single-domain approaches.

The framework integrates established models and assessment tools from DLR and European research initiatives with custom-developed SoS components. Validation follows a multi-tiered approach. First, model outputs are calibrated and verified using empirical aviation data, including emissions measurements, operational flight statistics, and socio-economic indicators. Second, results are benchmarked against established assessment tools and findings from major national and European research projects to ensure consistency and robustness. Finally, the framework is applied to representative case studies, including SAF adoption, contrail mitigation, and noise reduction measures. These applications assess the framework's ability to capture complex interactions and support evidence-based decision-making for sustainable aviation development.

3. Results / Conclusions

Demonstration studies conducted within national and European research projects validated key elements of the proposed framework in realistic aviation contexts. Preliminary impact assessments indicate that the Systems-of-Systems and digital engineering approach provides a structured means to evaluate environmental, economic, and societal impacts simultaneously. By capturing cross-domain interactions and trade-offs, the framework enables a more comprehensive assessment of aviation system transformations and supports

informed decision-making. These findings highlight the importance of holistic evaluation methods for identifying sustainable and competitive aviation pathways. Future work will further validate the framework through additional case studies, operational data, and emerging technology scenarios, strengthening its applicability for supporting robust aviation policy and industry decisions.

An Integrated Modeling and Dashboard Framework for Aviation Impact and Transformation Assessment

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1. Introduction / Objectives

The aviation sector is facing increasing challenges related to climate targets, energy transition, and economic uncertainty. Due to the strong interdependencies and coupling between technologies, vehicles, operations, infrastructure, and policy measures, integrated and transparent tools are needed to support future decision-making. As part of the DLR research project ALICIA (Aviation Life Cycle and Impact Assessment), an integrated multilevel framework and its web-based dashboard front end are being developed to provide accessible, data-driven insights into future aviation scenarios and DLR research outcomes.

2. Methodology

The presented approach combines interactive data analytics with an integrated aviation system model in a user-friendly dashboard environment. The framework couples multi-domain models with expert-in-the-loop capabilities, integrates models and datasets from various DLR research activities, and combines them into a common scenario analysis platform. The front-end dashboard enables stakeholders to evaluate and explore scenario outcomes in an accessible and interactive way. Existing modeling domains include air traffic forecasts, fleet dynamics, aircraft performance, operational measures, and environmental assessment.

The latest developments focus on extending the framework toward additional cross-sectoral systems that are increasingly relevant for future aviation transformation pathways. These include energy supply chains, fuel production pathways and economic. By linking these domains within a unified modeling environment, the framework enables the analysis of interactions and dependencies between aviation demand, technology development, energy production, and economic impacts.

Through the dashboard interface, users can define and compare custom scenarios by adjusting technological, operational, and policy-related assumptions. The application provides real-time feedback through interactive visualizations and comparative analyses, enabling transparent exploration of system-level effects and trade-offs across different future pathways.



Figure 1. *Overview of the Integrated Scenario Analysis Framework*

3. Results / Conclusions

Initial case studies demonstrate the potential of the framework to assess the impacts of different aviation transformation strategies on emissions, climate impact, energy demand, fuel supply requirements, and cost-related indicators. The integrated approach highlights the importance of considering interactions between aviation, energy, and economic systems when evaluating future pathways. The presented dashboard application supports transparent scenario exploration and aims to provide a flexible decision-support environment for research, industry, and policy stakeholders.

System Dynamics and Game-Theory Modelling for Multi-Stakeholder Competitive Analysis in System of Systems Aviation Impact Assessments

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1. Introduction / Objectives

The aviation sector is a hard-to-abate system of systems balancing sustainability and competitiveness across a tightly coupled stakeholder landscape of airlines, Original Equipment Manufacturers (OEMs), airports, and regulators. Despite advances in strategic modelling, a critical gap remains: no existing SoS framework simultaneously captures multi-stakeholder interactions, dynamic market feedbacks, and strategic equilibria under disruption. Limiting existing frameworks application for robust impact assessments and decision-making under uncertainty and competition.
This work addresses the research question a) What methodological gaps exist in current aviation impact assessment frameworks with respect to dynamic multi-stakeholder competitive modeling & assessments on a System-of-Systems level, and b) how can SoS dynamic simulation and game-theorey methods be operationalized to close these gaps? To this end, a systematic literature review maps structural limitations in current methodologies, followed by a proof-of-concept competitive model demonstrated in monopoly and duopoly aircraft market setup.

2. Methodology

The study proceeds in two stages: a systematic literature review followed by computational model development.
A Systematic Literature Review was conducted covering studies at the intersection of aviation impact assessment, SoS modelling, and game-theoretic approaches. The scope was iteratively expanded to include geopolitical modelling in engineering contexts, motivated by early findings revealing strong interdependencies with global energy markets, international trade, climate policy, and exogenous disruptions. Studies were categorized along two dimensions: methodological approach (simulation-based, analytical, empirical) and stakeholder coverage (single-actor, multi-actor). This dual classification surfaces where gaps in dynamic, multi-stakeholder representation are most pronounced. And where SoS methods that are capable to capture such interconnections are underused or systematically limited. **The first model tier** captures the airline–OEM relationship as a two-player SD–Nash structure: one airline and one OEM. The stock variables (order backlog, production capacity, fleet size, market price) evolve through first-order adjustment processes with across a configurable simulation horizon and integration step size. At each time step, the SD stocks are first updated via Euler integration, propagating all flow variables forward before the Nash layer is started. The Nash layer then solves a simultaneous best-response problem: the OEM maximizes margin on delivered units subject to capacity constraints, while the airline trades off fleet utilization against acquisition cost (see Figure 1). The resulting Nash equilibrium (Nash price, airline order volume, and OEM delivery quantity) feeds back into the SD stocks for the subsequent time step, closing the SD–Nash loop. Several scenarios can be examined e.g. Baseline (default parameters), Crisis demand shock, Agile OEM (shorter capacity response time), allowing direct comparison of SD-only versus SD+Nash trajectories.
The second model tier extends the framework to a three-player game: two competing OEMs and one representative airline. Each OEM faces both a capacity-constrained production

schedule and a competitive price-setting problem. With the airline's optimal order split determined by relative price and delivery-time attractiveness. This configuration produces endogenous market prices that are no longer anchored at the monopoly reservation level, demonstrating that competition alone can replicate price moderation without regulatory intervention.

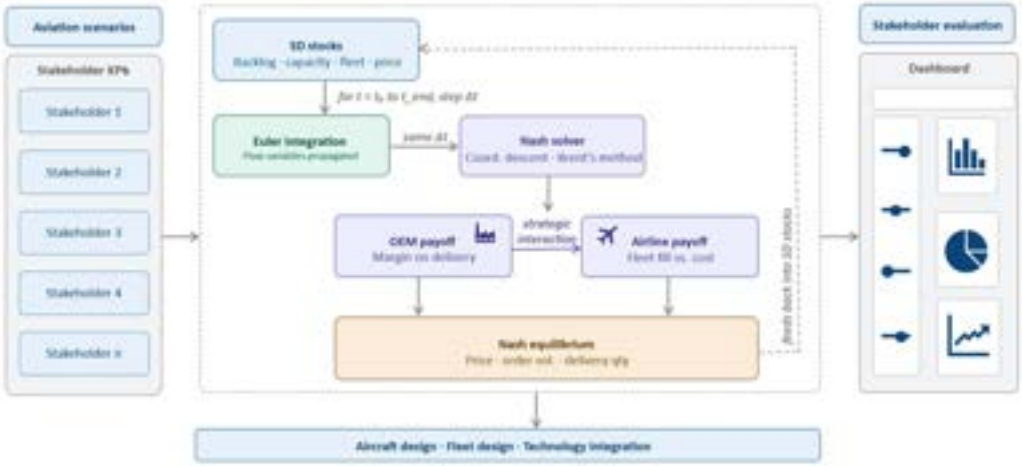


Figure 1. *SD+Nash integration loop (per timestep)*

3. Results / Conclusions

The literature review confirms a systemic underrepresentation of dynamic multi-stakeholder interactions in aviation impact assessment: geopolitical and disruptive factors are typically treated as static assumptions, and no unified framework simultaneously captures sustainability and competitiveness under multi-actor strategic dynamics using SoS simulation methods. The SD–Nash models directly operationalize this identified gap. Nash pricing yields a strategic premium of 8–15% above the SD equilibrium, amplified under the Crisis scenario; supply-side responsiveness proves more effective than demand management in dampening volatility. In the duopoly, competitive pressure drives Nash prices toward marginal cost more rapidly than fleet-adjustment dynamics alone predict. These results validate the conceptual framework and demonstrate its potential as a decision-support tool, generating actionable insights for stakeholders and regulators pursuing sustainable, competitive aviation.
Three future research directions emerge: extension to agent-based and discrete-event simulation, inclusion of additional stakeholder layers, and coupling of market dynamics with aircraft and fleet design with technology integration.

A Novel Taxonomy for Aviation Emissions Models

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1.Introduction / Objectives

The precise quantification of air transport environmental impact forms the basis for corporate travel carbon accounting, carbon credit trading or offset purchasing, aircraft trajectory

optimisation and consumer decision-making. However, the fuel consumption and emissions calculators in use today form a fragmented landscape. On the one hand, the underlying methods are scattered across academic publications, state-sponsored air-navigation tools (such as Eurocontrol BADA), intergovernmental calculators (such as the ICAO Carbon Emissions Calculator), and commercial providers (such as atmosfair, myclimate or the Google Travel Impact Model). On the other hand, they differ in scope and implementation and often rest on incompatible boundaries, with some considering tank-to-wake emissions and others well-to-wake emissions. Finally, they must satisfy different reporting standards (such as ISO 14083, ISO 14040/44, GHG Protocol, CORSIA) that again differ in boundary and accounting. What is missing is a principled way to choose between them – and a model accurate enough to serve them all. We therefore (i) systematically compare existing models and map them to reporting requirements in a taxonomy; (ii) showcase JetFuelBurn, a high-accuracy analytical model based on recent relations of Poll & Schumann; (iii) benchmark against proprietary airline data; and (iv) propose avenues to steer development toward the taxonomy's under-served parts.

2.Methodology

We classify aviation fuel consumption and emissions models along two axes: their computational complexity and how closely their assumptions approximate a real flight. **Figure 1** illustrates this for a single flight. The simplest models assume an ideal trajectory at zero-wind along great-circle path (Panel A). The most sophisticated models consider actual trajectories, including cruise-level winds vectors, temperature and the impact of non-CO_2 climate effects such as contrail formation and atmospheric chemistry interactions in the upper atmosphere (Panel D).

To place every incumbent model on the taxonomy and allow for a systematic comparison, we re-implement the major models within a single open framework, our own open-source JetFuelBurn model [1], so that observed differences reflect method rather than implementation and each can be located objectively within the taxonomy. JetFuelBurn itself is analytical, developed from the equations suggested by Poll & Schumann, and benchmarked against proprietary airline quick access recorder (QAR) data.

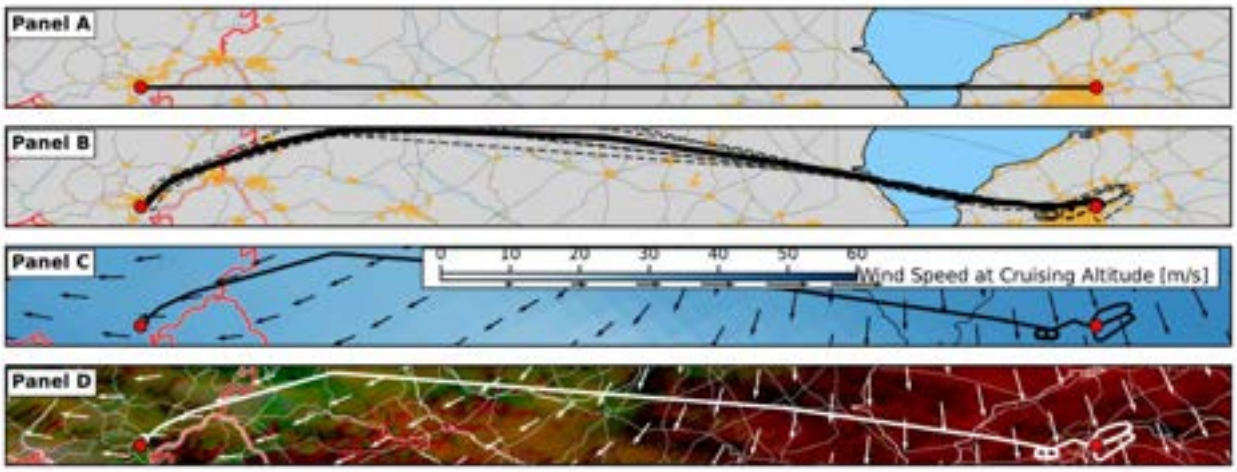


Figure 1. *Draft of a subset of the proposed taxonomy of aviation climate impact models, in ascending order of computational complexity, illustrated for a single flight from Zurich to London Heathrow.* ***Panel A:*** *An idealized flight assuming zero wind along the shortest possible path between origin and destination (great-circle distance).* ***Panel B:*** *An idealized flight again assuming zero wind, but along the average trajectory of past flights, thereby considering the impact of airways and great circle deviation due to, for instance, global conflict zones.* ***Panel C:*** *A real historical flight, considering effects of wind at cruising altitude. Wind vector field shown based on the ERA5 reanalysis model by the European Centre for Medium-Range Weather Forecasts.* ***Panel D:*** *A real historical flight, including both the effects of wind at cruising altitude and non-CO2 effects, such as contrail formation along the trajectory. Infrared cloud image based on NASA satellite data.*

3.Results / Conclusions

The proposed model taxonomy allows researchers and industry experts to objectively categorize aircraft fuel consumption and emissions model and to select the one whose system boundary and fidelity match their intended use. Mapping current models onto the taxonomy shows that most occupy only its low-fidelity end, being regression- rather than trajectory-based, and cannot represent real routing or prevailing winds.
We find that our JetFuelBurn model can reproduce airline flight-plan fuel burn more accurately than every regression calculator tested. Its relative error was on average <3% and below ±5% on all routes, whereas the legacy models reached errors of up to 48.7% on long-haul and 68.2% on short-haul. Crucially, our model simultaneously yields time-resolved fuel-burn, altitude, and radiative-forcing profiles. We therefore conclude that a single, open, physics-based formulation can replace today's patchwork of calculators across the entire model taxonomy.

Comparison of aviation mitigation strategies using customisable climate models

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1. Introduction / Objectives

Aviation contributes to climate change through CO_2 emissions and non-CO_2 effects such as contrail cirrus. A 2021 meta-analysis indicates that aviation accounts for 3.8% of the effective radiative forcing induced by human activities between 1750 and 2018. However, there are many uncertainties surrounding these estimates, and certain effects, such as aerosol-cloud interactions, were not yet quantified in this study. In any case, mitigating these impacts is required, and can be achieved by improving aircraft efficiency, enhancing operations, deploying alternative aviation fuels, managing demand, or offsetting. These different strategies can be analysed and compared directly by modelling transition scenarios. To this end, tools are needed to model these strategies and assess their associated climate impacts. The AeroMAPS framework was developed to address these issues.
The objective of this paper is to use this framework in order to compare several mitigation strategies often considered by aviation stakeholders by estimating their climate impacts. This will involve, in particular, taking into account the latest estimates of climate settings for aviation species drawn from recent academic literature, and assessing the impact on the ranking of mitigation strategies.

2. Methodology

AeroMAPS is an open-source Python framework structured to model air transport transition and its technical, environmental and economic impacts. The framework inherits from a multidisciplinary design and analysis optimisation backbone supporting model couplings and scenario optimisation. AeroMAPS includes a stand-alone package dedicated to the use of aviation climate models, AeroCM. This package is built from previous developments and currently integrates several types of climate models: metric-based (e.g. GWP*, LWE), analytics (e.g. IPCC) and emulators (e.g. FaIR). The models are standardised to allow for direct comparison across a given inventory, notably by incorporating default settings for aviation climate species (e.g. sensitivity to emissions, efficacy).
In this work, we have improved the current package and associated models. In particular, we have added dedicated species for aerosol-cloud interactions, a specific species related to ground H_2 leakage using data from Sand et al., and a new calibration regarding the effects of vPM and nvPM on contrails. These modifications have made it possible to test recent alternative values to those published by Lee et al. for contrails and aerosol-cloud interactions. Finally, for the FaIR climate model, we have also included a saturation factor for contrails and a dependence of aviation NO_x emissions climate impacts to background NO_x.

3. Results / Conclusions

Some illustrative results obtained with the updated AeroMAPS/AeroCM (with the FaIR climate model) framework are briefly presented. On the one hand, three climate configurations have been considered with AeroCM: a default one (corresponding to Lee et al. settings), a second one including a new calibration of the effect of vPM on contrails, and a last one assuming more recent species settings mentioned previously. On the other hand, three mitigation strategies have been considered in AeroMAPS: a baseline scenario only including aircraft efficiency improvements, a second one introducing sustainable aviation fuels (SAF) assuming the ReFuelEU blending mandates at the global scale, and a last one integrating contrail avoidance strategies. Figure 1 illustrates the results obtained at the temperature level, showing the importance of the climate settings regarding the ranking of the mitigation strategies.

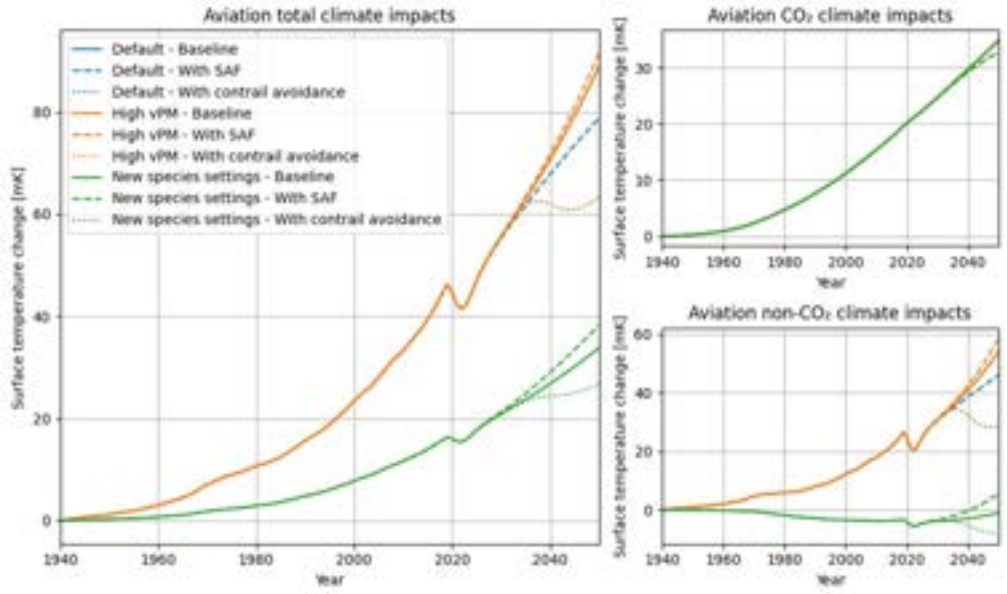


Figure 1. *Comparison of two mitigation strategies with a baseline scenario for three alternative climate settings.*

Note that the modelling effort presented is complete (except for H_2 leaks currently being investigated), and that the final application presented to the EASN conference will include numerous comparisons of strategies (H_2 aircraft, SAF, contrail avoidance, hydroprocessed kerosene, offsetting).

From Scouting to Assessing the Long-term Systemic Climate Leverage Potential of Emerging Technologies for Aviation

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1. Introduction / Objectives

Early identification of step-change technological advances from the global research landscape is essential for setting strategic direction toward climate-neutral aviation. Achieving this transition requires the use of 100% renewable energy while simultaneously leveraging further efficiency gains and therefore depends on coordinated progress in domains like energy, materials and information. To address this challenge, Bauhaus Luftfahrt applies its multi-step Technology Radar approach combining proven analytical methods and interdisciplinary expertise to identify and evaluate emerging technologies within a broad spectrum extending beyond classical aeronautical disciplines. This approach is transferred to the national level within the German LuFo VII-2 ATLAS project involving twelve research organisations. This work presents a novel approach for quantitatively comparing the long-term systemic climate leverage potential of fundamentally different technologies for aviation based on the ATR_{100} fleet reduction potential as a universal climate impact metric while accounting for scalability and integration constraints, and applies it to jointly scouted technologies.

2. Methodology

The established Bauhaus Luftfahrt Technology Radar approach is being implemented consortium-wide within the ATLAS project (see Figure 1). To enable systematic assessment within such a large group of experts, a novel multi-step, multi-criteria evaluation methodology was developed for consistently comparing, downselecting and prioritising emerging technologies from a broad spectrum with respect to their systemic climate mitigation potential for subsequent detailed evaluation and risk assessment.
Within a first project sprint, the process comprised technology scouting, consortium-wide review and expert exchange, initial assessment and pre-prioritization of identified developments to converge on the most promising candidates. This process resulted in a dedicated Downselection Workshop involving around 60 participants from the ATLAS consortium. The workshop combined standardized technology pitches designed to provide a consistent and decision-relevant overview linking physical principles, mission-level effects and climate impact with poll-based evaluations and moderated discussions to ensure comparability between diverse technologies. In particular, the degree of divergence and uncertainty within the poll-based assessments was explicitly analysed in real time during the workshop and used to guide and focus the subsequent expert discussions.
For systematic and comparable evaluation, technologies were categorized according to their primary climate impact mechanism, including direct efficiency improvements, e.g. through propulsion, aircraft configuration and system optimization, enabling technologies for alternative propulsion and energy systems, as well as operational measures for climate impact reduction. The methodology integrates climate-relevant criteria including applicability of the technology to different flight segments, achievable magnitude and scalability of effects, as well as expected practical integration penalties. These were systematically assessed based on standardized technology pitches and structured poll-based expert evaluation and subsequently integrated into the ATR_{100} fleet reduction potential metric. The resulting ATR_{100} metric serves as a unified basis for comparing the fleet climate impact reduction potential of different technologies while accounting for both theoretical potential and practical implementation constraints.



***Figure 1**: Consortium-wide implementation of the interdisciplinary multi-step Bauhaus Luftfahrt Technology Radar approach within ATLAS for the identification and assessment of high-priority technological advances toward climate-neutral aviation.*

3. Results / Conclusions

The consortium-wide implementation transferred the established Bauhaus Luftfahrt

Technology Radar approach to the national level within a large interdisciplinary research consortium. The results demonstrate that the novel assessment framework enables transparent and consistent comparison of physically diverse technologies based on a universal climate impact metric. Technologies with the highest leverage were identified as those strongly enabling alternative propulsion and energy systems capable of mitigating both CO_2 and non-CO_2 climate effects while being applicable to a broad range of aircraft segments, thereby offering particularly high potential for supporting the transition toward climate-neutral aviation (see Figure 2). These were followed by technologies enabling direct mission fuel reduction with favorable scaling properties and high expected remaining effects after practical integration. The resulting prioritisation provides strategic guidance for future aviation research and supports subsequent in-depth evaluation of selected high-leverage technologies. The Technology Radar approach further shows strong potential for application in international expert networks across Europe and beyond.

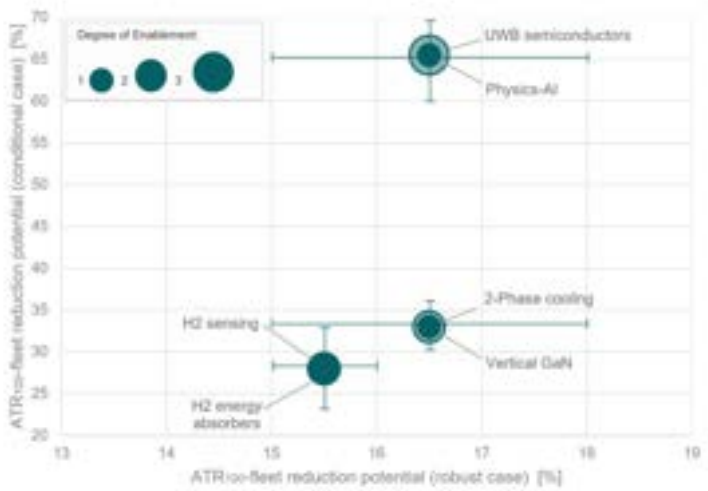


Figure2: Selected results for enabling technologies supporting alternative propulsion and energy systems, showing robust versus conditional ATR_{100} fleet reduction potential. High-leverage technologies enable hydrogen-based propulsion and are applicable on multiple aircraft segments. "Robust" denotes near- to mid-term potential, while "conditional" reflects long-term potential dependent on successful technology and system scaling, including further technology breakthroughs

Impacts of Contrail Accounting in the EU ETS: A Large-Scale Analysis of European Operations in 2018

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1. Introduction & Objectives

CO_2 emissions account for only one-third of aviation's climate effect, whereas a majority is expected to be caused by non-CO_2 effects like contrail cirrus and nitrogen oxides associated with larger quantification uncertainties. Consequently, the European Union (EU) revised its Emissions Trading System (ETS), requiring aircraft operators to monitor and report

total climate effects and provide CO_2 equivalent (CO_2e) emissions per flight since January 2025. By December 2027, the EU might propose further legislation, e.g., introducing non-CO_2 pricing to incentivize mitigation, which might affect operators, influence ticket prices and encourage climate-optimized routings. To assess the influence of non-CO_2 accounting on routings, mitigation potentials and costs across Europe, we extend previous mission-specific case studies to a day-by-day analysis of 2018 using actual weather data. By doing so, we aim to assess the suitability of such a policy approach to incentivize implementation of trajectory optimization to reduce non-CO_2 effects.

2. Methodology

Climate-optimized flight planning typically balances two possibly conflicting objectives: minimizing operating costs and reducing the overall climate impact. CO_2e-based accounting creates an economic incentive to re-route flights and simplifies considerations to a single-objective, i.e., minimizing direct operating cost (DOC) in dependence of fuel burn m_{fuel}, flight time t and the mass of CO_2e emissions m_{CO_2e} based on cost indices c_i:

$$DOC = c_{fuel} \cdot m_{fuel} + c_{time} \cdot t + c_{CO_2e} \cdot m_{CO_2e}$$

In contrast to previous studies, we focus on the analysis of contrail mitigation modelling with CO_2e accounting of contrail climate effects. Based on CO_2e estimates from algorithmic Climate Change Cost functions, this study aims to assess and compare trajectory optimization results for the following optimization set-ups:

(i) Business-as-usual: Trajectory optimization targeting DOC excluding accounting of non-CO_2 effects ($c_{CO_2e} = 0\ EUR/kg_{CO_2}$)

(ii) Climate-optimized routing: Trajectory optimization minimizing contrail distance in dependence of DOC penalty excluding CO_2e accounting ($c_{CO_2e} = 0\ EUR/kg_{CO_2}$)

(iii) Non-CO_2 accounting: Trajectory optimization targeting DOC including climate cost from CO_2e accounting ($c_{CO_2e} = 0.08\ EUR/kg_{CO_2}$)

For this purpose, we use a method introduced by Yamashita et al. (2020) using the EMAC (ECHAM/MESSy Atmospheric Chemistry) model including submodules CONTRAIL, ACCF and AirTraf [3-6]. AirTraf optimizes aircraft trajectories using a genetic algorithm solving single-objective problems in cases (i) and (iii) or multi-objective problems as in case (ii). The optimization in this study is performed for a full year of operations by including weather information over the year 2018. The flight sample includes 100 representative European routes focusing on warming contrail conditions, and using the A320neo as a reference aircraft.

3. Results and Outlook

Preliminary results from the large-scale analysis comparing optimization set-ups (i) and (iii) confirm the results obtained from the conceptual study by Niklaß et al. (2025). Figure 1 illustrates the climate impact in average temperature response over 100 years for a pulse-emission scenario (p-ATR100) from emission species CO_2 and contrail-cirrus over the year 2018. For all monthly averages, we find that non-CO_2 pricing effectively reduces the climate impact through persistent contrail avoidance. Large reductions in climate impact are typically associated with larger fuel burn penalties. Seasonal variations can be observed but need to

be interpreted with care due to limited applicability of the contrail aCCFs which was developed for winter month only.

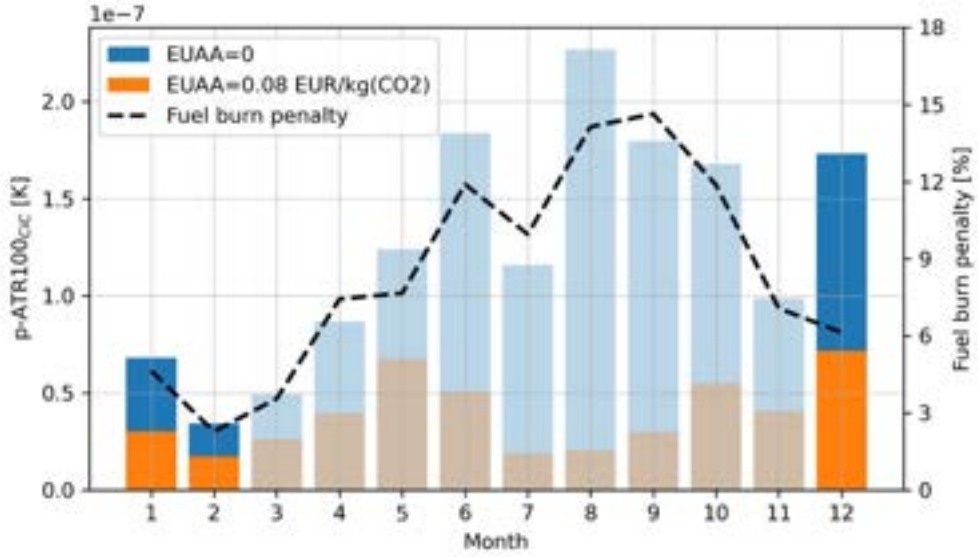


Figure 1: *Contrail climate impact in dependence of the accounting scheme and associated fuel burn penalty for monthly averages of 2018 for 100 representative European routes. Shaded areas represent out-of-scope application of aCCFs.*

Final results of this paper will comprise a detailed analysis of results for different seasons, possible influences on ticket prices and operators as well as a detailed comparison between cost and climate-optimization set-ups. Uncertainties of the assessment especially in context of non-CO_2 climate effects will be discussed.

Acknowledgement: This work is part of the EU Horizon project Better Contrail Mitigation (BECOM), funded by the European Union (Grant agreement ID 101056885).

LOCAL AIR QUALITY ASSESSMENT FOR UPDATED AIRPORT FLEET via EFACA and SENECA AIRCRAFT

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1. Introduction / Objectives

Climate change is the definitive megatrend shaping the aviation industry. To stay within the 1.5°C warming limit, the ICAO basket of measures targets fuel burn reduction via aircraft technology (up to 25%), operational improvements (up to 9%), sustainable aviation fuels (SAF) and market-based incentives to accelerate implementation.
Radically new, innovative aircraft concepts are needed to ensure increased fuel efficiency

and emissions reduction. Sustainable innovations drive next-generation aviation via electrification and alternative fuels, including hydrogen. Thus, the EU EFACA project focuses on the implementation of hybrid-electric propulsion in combination with fuel cells for propeller-driven regional aircraft, as well as a liquid hydrogen fuel system for airliners. Regarding new supersonic aircraft, future technologies primarily focus on traditional emission reduction methods in combination with SAF to lower engine fuel burn (EU SENECA project). This paper demonstrates the results of the emission assessment for hybrid, hydrogen (EFACA), and supersonic (SENECA) conceptual aircraft at both aircraft and airport levels.

2. Methodology

PolEmiCa (Pollution Emission Calculations) model was used for calculation emissions for conceptual EFACA/SENECA aircraft. PolEmiCa uses the BFFM2 and P3T3 methods to predict engine emissions over a flight path based on flight conditions (flight profile data), engine performance data (fuel flow, fuel-air ratio, P3, T3) and meteorological conditions (temperature, humidity, atmospheric pressure).
At airport level PolEmiCa model was used mainly for the aircraft emission and air pollution calculations during the LTO cycle of the aircraft movement inside the airport area, figure.1. It consists of the following basic components:

1.engine emission model provides emission factor assessment for aircraft engines, including influence of operational and meteorological factors by BFFM2 and P3T3 methods;

2.jet transport model evaluates basic mechanisms of contaminants transportation and dilution by the jet from the aircraft engine exhaust providing basic parameters of the jet, as vertical and horizontal dispersion of plume (σx, σy, σz) and its buoyancy effect for further assessment of the instantaneous/averaged concentration;

3.dispersion model calculates the d concentration taking into account the atmospheric turbulent diffusion and wind transfer.

Basic expression for definition of maximum instantaneous value of concentration in grid point is a solution of turbulent diffusion equation according to Eulerian/Gaussian approach for moving point source with preliminary transport and dilution of contaminants by an exhaust gases jet and atmospheric turbulence. PolEmica is a customized GIS application based on QGIS to process the different types of the emission sources estimates into a standard format in preparation of dispersion modelling.

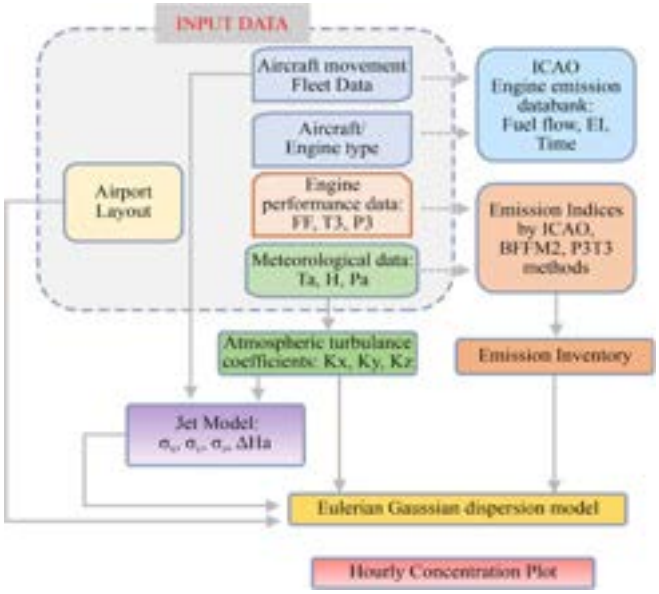


Figure 1. PolEmiCa integrated model for airport air quality

3. Results / Conclusions

Emission indices of NOx, CO and HC were calculated throughout the flight profile assessment for hybrid, hydrogen (EFACA) and supersonic (SENECA) conceptual aircraft. The efficiency of the SENACA and EFACA aircraft are assessed by comparison with reference aircraft, which are defined as a best-in-class aircraft currently. Every reference aircraft model is verified with measurements done in airport in real operational conditions.

Three scenarios were defined for local air quality (LAQ) studies at the airport (CAEPport) level:

- *Baseline Scenario*: The conventional aircraft fleet for CAEPport, incorporating the Concorde in the large aircraft category, the ATR72-600 in the turboprop category, and the A320neo in the small aircraft category;
- Predicted Scenario: an updated fleet for CAEPport, including the M1.8 supersonic airliner (SENECA aircraft), the An300 (hybrid turboprop EFACA aircraft) and the An200H2 (hydrogen EFACA aircraft).

Based on these scenarios, the aircraft emission inventory and hourly NOx concentrations were calculated using the PolEmiCa model for both the baseline (a reference case with reference aircraft in fleet) and updated (a forecasted case with conceptual aircraft in fleet) and updated fleets.

Validation of Contrails predictions with Ground Observations

Tanguy CHAUVET, Romain MOREAU, Thomas MENAGE-BRINSTER, Corentin GHESTEM, Maryam BOUJDAA, Bernard MOUTON, Pascal MAURER, Clément LANGOLFF
SII Group, France

1. Introduction / Objectives

The non-CO2 effects of aviation are a vast topic still under study by academics and industrials. Namely, the community is still active to fully understand the impact of persistent contrails formed by cruising aircraft in specific atmospheric conditions. One of the complexities of the subject is the prediction of the formation of a persistent contrail by an aircraft. The European Commission is building a non-CO2 ETS regulation that needs to be based on consolidated knowledge.
Our study aims at contributing to global contrail research, to compute contrail predictions and detections as well as providing an interface displaying contrail observations along with contrails predicted by models.
Ultimately, our objective is to improve the automatic detections of contrails as well as to provide statistics of contrail prediction model results, based on accessible ground truth.

2. Methodology

The objective defined by SII Research is to provide comparisons between contrails formed and model predictions on past flight data with multiple partners.
We collaboratively define cases from acceptable weather conditions and therefore select suitable time periods to observe aircraft in cruise from the ground. Associated time-windows allows to list flights crossing the observation field of selected ground-based imager.
Then, we collect the real trajectory flown on the given cases. Then, the associated images taken from the ground are provided by the partners Eurocontrol and Reuniwatt. In parallel, we use the most widely used contrail prediction model, called CoCiP. We transform the result of Energy Forcing given on the segment of the trajectory into polygons that are advected with the wind of the day.

Our steps are the following:

1. Using visible or thermal-infrared images (from Eurocontrol or Reuniwatt), we manually label or detect with a computer vision model. We detect the contrails in the form of a polygon and project them using imager calibration
2. We compute contrail predictions using Contrail Cirrus Prediction (CoCiP) from Pycontrails with Poll-Schuman / BADA aircraft performance model and ERA5 reanalysis weather data, then project the resulting predictions as polygons on a map
3. Attribute observed polygons to predicted ones for comparison, using synchronization between the polygons on the map and the images through a timeline to see the aircraft traffic and contrails advection
4. Statistics to evaluate the contrail prediction model through a comparison of the observation and the associated prediction



Figure 1. *Contrail Tracker presenting predicted contrail on the left and detected contrail on the*

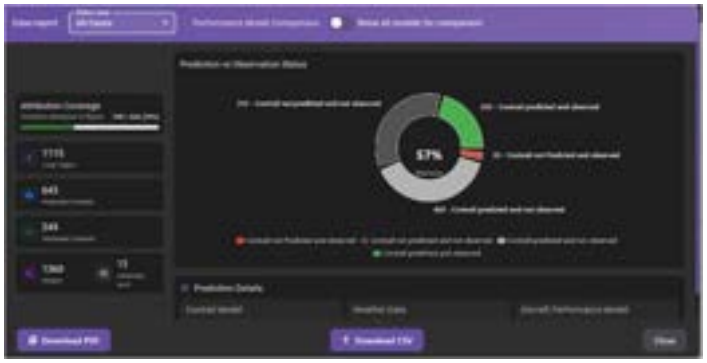


Figure 2. *Reports of comparison between predicted and observed contrails*

3. Results / Conclusions

In our current stage of May 2026, from the two different sources of 1360 images, we computed contrail predictions on 1115 flights crossing the field of view of Toulouse and Bretigny sites, for which 645 contrails were predicted, and 249 have been observed and attributed to their flights.

This represents a 57% model relevance with the conditions of observations, the available weather data and the parameter of predictions used on the model.

This is an intermediary result that will be improved once our interface is used by many other actors such as Airbus, Dassault and Onera in the next years, as discussed currently.

A simulation tool for airport flight operations

Jordi Pons-Prats, David De la Torre
Universitat Politècnica de Catalunya, Spain

1. Introduction / Objectives

The Impact Monitor 2 is a European project aimed to deliver a holistic toolbox and framework, which enable the impact assessment of new technologies. In parallel to the development of the framework and integration of the already available tools, some effort has been also devoted to the development of complementary tools to those already proposed. In the particular case described in this communication, the simulation tool complements DYNAMO, a trajectory simulator and predictor. It lacks the landing and take-off operations, which are the main target of the tool called SILVER. The contribution is based on the capability to simulate not only landing but also take-off, rejected take-off (before and after V1) and go-around operations. These simulations can be used either for the definition and/or validation of the declared distances, or for safety purposes calculating the required operational distance under specific circumstances. Based on BADA database, the tool considers realistic and industry-standard modelled performance of aircraft and it also enables to compute the fuel and emissions for these operational phases.

2. Methodology

In order to simulate the landing and take-off operations, including emergency situations, each operation is divided into several phases, which helps to apply specific details and parameter values. The implementation is based on the definition of the following phases; glide, flare, rotation, and deceleration for landing, acceleration, rotation and lift-off for take-off, acceleration and deceleration for the rejected take-off before V1, the acceleration, rotation and lift-off for the take-off with and engine failure (after V1), and glide, (flare and acceleration) and climb for the go-around. Some of these phases follow the same rules, only adjusting the conditions (thrust level, stop conditions, for instance).
As proposed, the implementation proposes a set of governing equations which are adapted to each phase. The equations state:

$$\frac{dv}{dt} = \dot{v} = \frac{T - D(v,h,s,C_l,\beta) - \mu \cdot N}{m} - g \cdot sin(\gamma) \qquad \frac{d\gamma}{dt} = \dot{\gamma} = \frac{g}{v} \cdot (n_z \cdot cos\phi - cos\gamma) \qquad \frac{dh}{dt} = \dot{h} = v \cdot sin\gamma$$

$$\frac{ds}{dt} = \dot{s} = \sqrt{v^2 \cdot cos^2\gamma - W_x^2(h,s)} + W_s(h,s) \qquad \frac{dm}{dt} = \dot{m} = -q(v,h,s,T)$$

The state vector $x^{(i)}(t) = [v, \gamma, h, s, m]$ contains the velocity, flight path angle, altitude, distance and mass. The control vector defines $u^{(i)}(t) = [T, n_z, \beta]$, containing the thrust, load factor and deployed aerodynamic devices. Finally, time independent parameters include wind conditions, altitude and velocity set up for glide, flare and take-off, decision speed and stop speed; $p^{(i)}(t) = [W_x, W_s, r_c, h_{glide}, v_{glide}, h_{flare}, h_{TO}, V1, v_{stop}]$.
The assumptions consider the use of a point-mass model, negligible bank and pitch angles, and constant wind conditions along the runway.
For the ground phases, the friction is added to the drag, so the tarmac friction coefficient is considered. Five different conditions of dry, wet, water, snow and icy tarmac can be applied, defining a different coefficient in each case. When simulating the two emergency situations that imply an engine failure, the degree of failure is assumed as a percentage of loss with regards to the total thrust.
As mentioned, pitch angle is considered equal to zero, but when dealing with the go-around operation, a punctual pitch angle different to zero is considered to simulate the change of attitude the pilot applies to restart the climb. This value can be set up by the user.
The load factor applies to the take-off weight or the landing weight, according to the simulated operation, as a percentage of the maximum weight of that operation. The altitude and velocity of the glide are considered on landing just over the threshold (50ft as default for the altitude), while altitude at take-off is the final altitude of 35ft (as default value). All the values in the vector $p^{(i)}(t)$ can be easily customized to assess their effect on the operation.

3. Results / Conclusions

The five operations have been successfully implemented. Results shown the evolution of force and mass parameters along the operation, as shown in **Figure 28**, where the mass decrease with the increase on the fuel consumption along take-off. A second set of results show the variability associated to specific inputs, like in **Figure 29**, where the runway conditions modify the distance required for each phase of the rejected take-off operation.

The tool is under validation, but is ready to be coupled with DYNAMO, and later with the Impact Monitor framework, helping to understand the capability of new entrants to safety

and sustainably operate in existing airports. The tool is ready to provide simulated data for any of the five flight operations, as a tool to validate the declared distances, or as a safety tool to assess the required distance under specific circumstances and weather conditions. As a research tool, it is under continuous development and improvement, adjusting the parameters and setup as accurately as possible to the real operation of aircraft.

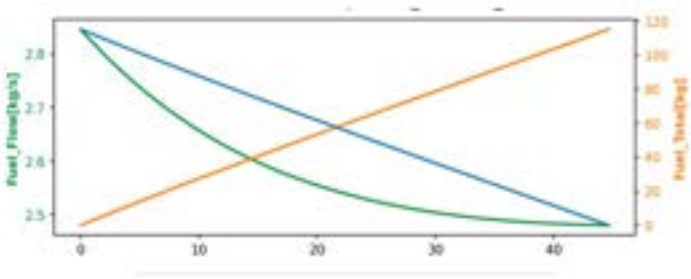


Figure 28. Analysis of mass during TO

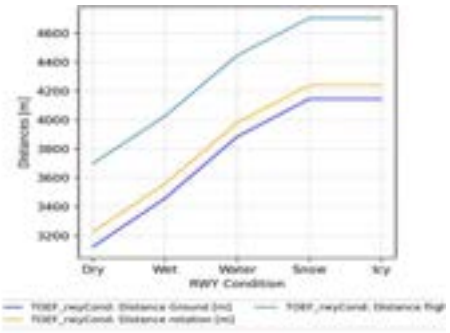


Figure 29. Variation of phase distance during rejected TO

HERWINGT Demos: Development Challenges and Solutions

Chaired by:
Mr. Sebastián Pellicer Sotomayor (Airbus Defence and Space)

Design, Analysis & Manufacturing of LRI Thermoset Leading Edge Demonstrator

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Hellenic Aerospace Industry, Greece

1. Introduction / Objectives

The scope of this study is to describe the Baseline Leading Edge Thermoset Leading edge structural design, analysis and manufacturing methodology of HERWINGT project funded by Clean Aviation Joint Undertaking under Grant Agreement No.101102010. The main challenge of these activities is the execution of one shot Liquid Resin Infusion (LRI) manufacturing process for a hybrid sandwich – LRI concept. Of course, the final configuration must withstand the aerodynamic pressure loads and comply with the bird strike requirements having also optimized weight.

2. Methodology

The workflow of the design process for the leading edge demonstrator as shown in Figure 1 is in summary:

- Definition of the preliminary CAD model of the leading edge.
- Leading edge structural optimization thickness definition according to aerodynamic load cases.
- Bird strike simulation activities.
- Updated FEM analysis.
- Detail design model (CATIA geometry).

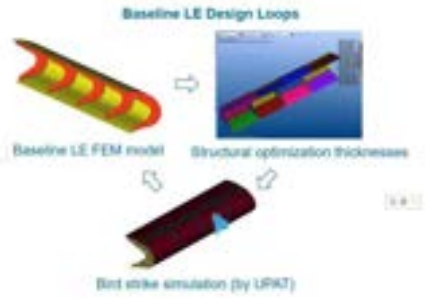


Figure 1. *Leading Edge Demonstrator structural design process*

Dry preforms of the carbon fabric material are prepared using the appropriate mold tools. Placement of the necessary auxiliary materials follows in order to complete the materials layup on the mold tool.
The setup used for the LRI process of the LE is shown in Figure 2 where a smaller (in length) LE demonstrator has been manufactured. It is important to note that due to the existence on the impermeable core material the flow media material has to be laid on both the IML & OML sides of the part, so that a complete impregnation of the part can be achieved.
The LRI process strategy is as follows: the resin is first infused at the lowest point of the LE tool/mold, between the two ribs through spiral runner tubes. The venting points are at the sides of the tool. When resin reaches the sides of the tool, then those venting points are deactivated and the venting points (which are on top the ribs) are activated so that the ribs' webs can be infused by resin and are free of air bubbles. Then, after a short while when ribs are filled with resin, venting ports on the top of the ribs are deactivated and respective venting ports that are located at the top edges of the LE mould are activated, until the whole part is filled with resin and is air free. The whole process has a duration of approximately half an hour. For this manufacturing trial, the materials selected in the HERWINGT project (ordered from HEXCEL) were used. The LRI process was also simulated using the commercial software RTM worx .



Figure 2. *Leading Edge Demonstrator LRI manufacturing process*

3. Results / Conclusions

In conclusion, the usage of LRI sandwich technology could improve the integration of composite solutions up to 5% in weight reductions. The weight improvement could be obtained if dynamic material properties instead of static (taken from either available literature or testing databases) – are used in bird strike simulation activities.

Shaping the Future of Wing Manufacturing: An Integrated Flap Upper Skin Demonstrator Based on Resin Infusion Technologies

José Martín Bravo, Rocío Palomo Vera, Luis Sepúlveda Ramos, Francisco Javier González González

Aciturri Engineering, Spain

1. Introduction / Objectives

The flap demonstrator focuses on the validation of advanced composite manufacturing technologies based on carbon fibre resin infusion within a single aeronautical component, developed in the framework of the HERWINGT programme (Grant Agreement No. 101102010). The infusion process enables the co-integration of key structural elements, including major parts of the skins, spars, and leading and trailing edges—into a highly consolidated structure, significantly reducing assembly operations and improving overall structural efficiency.

This manufacturing approach is implemented within an out-of-autoclave framework, representing a key step towards more efficient and sustainable aerostructure production by lowering energy consumption and manufacturing costs while maintaining stringent aeronautical requirements.

The HERWINGT project is supported by the Clean Aviation Joint Undertaking and funded by the European Union, contributing to the development of next-generation sustainable aviation technologies.

2. Methodology

The flap demonstrator methodology is based on an infusion-driven manufacturing approach focused on the highly integrated upper substructure. The tooling concept has been specifically developed to enable the manufacture of the upper structure as a single, highly integrated component, including the upper skin, leading edge, front spar, rear spar, and trailing edge through Liquid Resin Infusion (LRI). This approach targets the consolidation of multiple structural elements into a monolithic configuration, significantly reducing assembly complexity and improving structural continuity.

The manufacturing process involves the preparation and lay-up of dry fibre materials, followed by structural integration on the tooling. The assembly incorporates auxiliary materials and controlled resin introduction to ensure proper impregnation and consolidation of the component. Once completed, the part is infused and cured, and subsequently demolded, trimmed, and inspected to verify compliance with design requirements.



Figure 1. *Upper Skin LRI.*

In the final stages of the demonstrator, additional components are incorporated to complete the lower skin assembly. These elements, however, are not within the scope of the present work, which focuses specifically on the development and validation of the infusion-based upper structure.

3. Results / Conclusions

The flap demonstrator validates the feasibility of advanced LRI infusion technologies for the manufacturing of highly integrated aerostructures. The infusion process successfully enabled the production of an integrated upper structure, consolidating skins, spars and edges into a single component with good geometrical accuracy and surface quality, highlighting significant weight-saving opportunities.

The results confirm the capability of infusion-based manufacturing to achieve a high level of structural integration while maintaining dimensional tolerances and overall component quality.

Overall, the outcomes demonstrate the potential of out-of-autoclave infusion processes to reduce assembly complexity, lower production costs and lead times, improve structural efficiency, and enable more sustainable aerostructures.

Herwingt Pylon to Pylon demonstrator

Ana Rodríguez Henche[1], Alba López Ruiz[1], Sebastián Díaz[2]

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[2] MTorres, Spain

1. Introduction / Objectives

Herwingt Pylon to Pylon demonstrator intends a step forward in the application of Liquid Resin Infusion technology to torsion boxes.

Based on the achievements of CSK2, with the material under qualification, P2P aimed to go beyond in the thickness infusioned, the capacity of integrate components, and increase the complexity of the geometry including dihedral and sweepback angle.

The project is mainly focused in the development of manufacturing processes, the improvement of the hot forming and infusion tooling, and take the most benefit of the material capabilities, like the steering and easiness of element integration.

2. Methodology

Pylon to Pylon demonstrator is designed as a continuous wing box looking for a tip-to-tip wing. Eliminates the joints of skins and spars at the root joint what is a great benefit in terms of weight savings. This new design approach means that change of angles (dihedral and sweepback angle) has to be covered by fibre placement, that is why the design is based on the material steering capabilities. On top of that, the increase of thickness and the integration of the three spars with the lower skin are the basis for the design.

The manufacturing process of the lower integrated panel is the main challenge of the project. It is made in one shot process. Infusion and curing tooling are the same as assembly tool, it has the requirements of ensuring part final dimensions, tolerances and geometry because there is no further assembly of components, therefore not possible installation of shimming to compensate tolerances.

Tooling is made of carbon fibre with the objective of having same CTE (thermal expansion of material) to minimize part deformations.

Vacuum bag is one of the critical steps of the process, it is complex because includes the part and all the tooling inside; spars toolings are placed on both sides and they shall warrantee part geometry during all the infusion process.

In order to define properly the process and mitigate risks, the infusion has been simulated including the tooling constrains, the design and the material parameters, several studies has been carried out to optimize infusion and the global process.

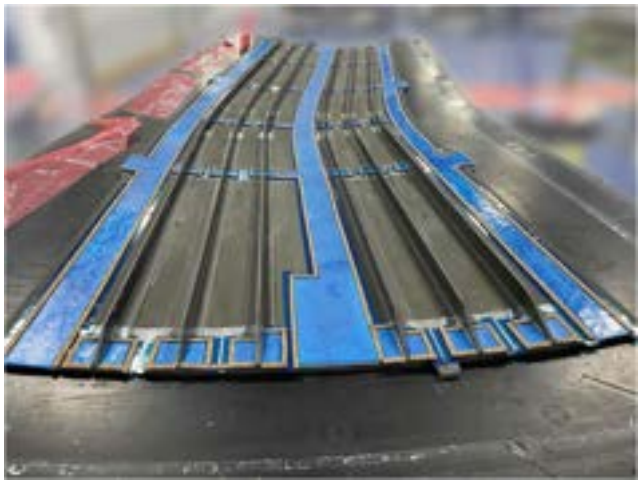


Figure 1. *Upper panel*

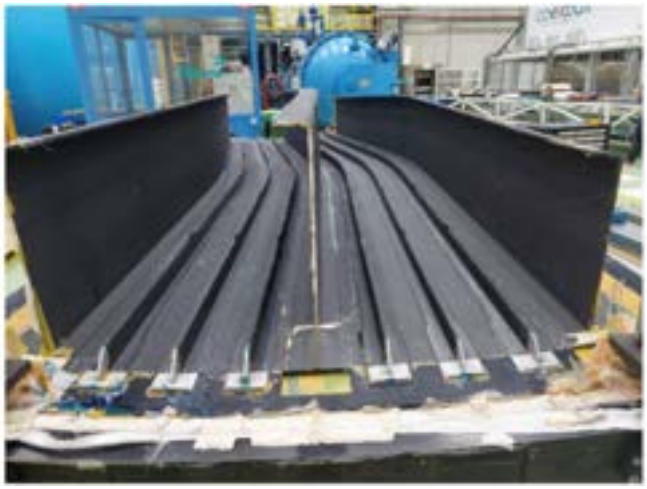


Figure 2. *Lower integrated panel.*

3. Results / Conclusions

The upper panel has been manufactured correctly, the tooling for hot forming and infusion did work properly, geometry of the part is in accordance with expected results from simulations, manufacturing processes were conform, updated and improved during the execution.

With the upper panel, including the skin and stringers, we can conclude that infusion of expected thickness is granted, simulations methods are good and tooling meets the requirements. In terms of steering capabilities, it is good, but with some improvements to be deeper analyzed.

Before lower panel execution, a 1 m long test was successfully done for lower panel configuration with the final tools of the project, proving that infusion of thick panels including wide spars is also achievable.
For the lower panel manufacturing, which includes also the spars, the results for the full-size part were not as expected, in contrast with the 1m part. The hot forming of parts was performed properly, but some wrinkles were found in spars, even though de-risking spars were done in advance. Deeper analysis is being performed to understand the origin.
Vacuum bag was as complex as expected, even taking into account knowledge from upper panel, it is one of the critical steps in the process. The infusion was not performed according to simulation forecast, infusion lead time was really tight with only one infusion machine, the reality showed that the resin flow was not good enough at the end of the process, and some areas got dry. That makes this first part manufactured not valid for further testing.
Unfortunately, there is no budget nor time enough for a second part execution.
First execution of lower panel allows to validate the tooling concept, the process to integrate spars, thickness, deformations and process simulation, and guide us to the following steps to mature the technology, mitigation of wrinkles in the spars, deep analysis of steering capabilities.
As lessons learnt for future research opportunities, we would highlight that when going for such complex component including several techno steps, it is key planning properly the global pyramid testing for small components, in advance or in parallel, and save budget and time for at least two specimens manufacturing on the critical processes, as was the baseline in Herwingt, cause the risk of failure at first manufacturing is high.

A Scalable Resistance Welding System for Thermoplastic Composite Leading Edges: From Laboratory Optimization to Full-Scale Demonstrator Assembly

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1. Introduction and Objectives

The HERWINGT project, part of Europe's Clean Aviation initiative, wants to help decarbonize aviation by designing new wings for future hybrid-electric regional aircraft . To make airplanes lighter and more efficient, the industry is moving away from traditional thermoset materials and shifting toward high-performance thermoplastic composites (TPCs). Thermoplastics are tough, can be manufactured faster outside of an autoclave, and crucially, they can be welded together instead of using heavy metal rivets. This study looks at a specific, difficult problem: assembling a wing leading edge, which is highly curved and has very tight internal spaces. Our main goal was to build a robotized resistance welding system that can fit into these small spaces, adjust to the complex shapes, and apply the exact right amount of heat and pressure to get a perfect bond.

2. Methodology

The experimental methodology centers on a novel robotized resistance welding head integrated into a flexible, scalable platform designed for restricted structural workspaces. As shown in **Figure 1**, the specialized hardware consists of an upper moving welding head and a lower modular tooling fixture. The welding head features independent pressure

components that precisely follow the steep, parabolic curves of the wing leading edge. At the core of this system are customized multi-zone heating elements placed along the welding interface. These elements deliver variable, localized power levels across a single, complex geometry. This multi-zone capability is crucial because the leading-edge skin and internal structural ribs do not have a constant thickness. In conventional welding, varying thicknesses cause uneven heat dissipation, leading to overheating or uncured zones. By adjusting the electrical power locally, this configuration compensates for thermal gradients and ensures a uniform temperature field. The physical welding sequence relies on continuous pneumatic and mechanical force tracking. During the process, the upper robotic head lowers into the U-shaped tooling block to clamp the carbon-fiber/thermoplastic composite (PEEK/CF) parts together (see **Figure 1**). To handle manufacturing tolerances and surface irregularities, the system uses an automated pneumatic loop to constantly re-adjust the mechanical pressure on each individual point along the curve. To drive the process toward zero-defect manufacturing, we implemented a real-time control loop architecture. The software continuously monitors electrical current, welding time, and interface pressure, automatically adjusting the power input on the fly to prevent defects. Finally, to validate the system under realistic factory environments, a multi-physics testing campaign was conducted. This included electro-thermal evaluation via infrared thermography to map heat distribution, followed by mechanical testing and microscopic characterization of the PEEK/CF welded joints to assess structural consistency.

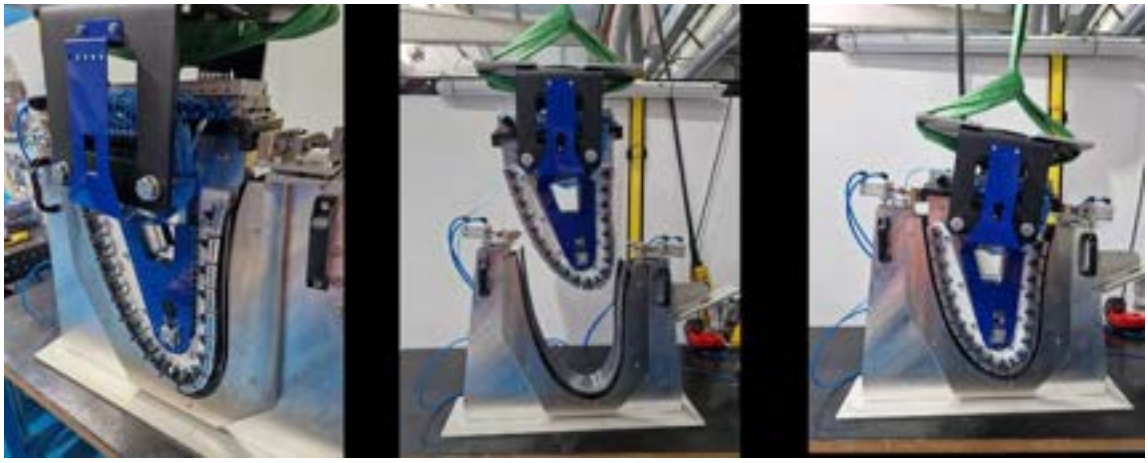


Figure 1.*Experimental setup of the robotized resistance welding system showing the flexible tooling and the assembly steps of the leading-edge demonstrator component..*

3. Results

The validation of the advanced welding head in realistic conditions demonstrated precise geometry adaptation over the high-curvature profile of the leading edge. The customized heating elements successfully delivered tailored thermal inputs, mitigating overheating risks in transition zones. Multi-zone power tracking ensured a uniform temperature distribution at the welding interface, leading to highly consistent joint consolidation. Mechanical testing of the

welded carbon-fiber/thermoplastic samples revealed high lap shear performance, satisfying the demanding requirements of aerospace structures. These outcomes validate the transition of sequential resistance welding from lab-scale cells to a highly scalable, automated industrial solution, paving the way for sustainable, efficient manufacturing lines for next-generation commercial aircraft.

From Conceptual Design to Preliminary Functional Testing: Development and Experimental Maturation of a Morphing Trailing Edge Flap Demonstrator

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[2] EuroTech S.R.L., Italy

1. Introduction

Morphing technologies are increasingly recognized as key enabling solutions for improving aerodynamic efficiency and supporting the development of future sustainable aircraft. Within the Clean Aviation HERWINGT (Hybrid Electric Regional Wing Integration Novel Green Technologies) project , a compliant Morphing Trailing Edge Flap (MTEF) has been conceived and developed to enhance the aerodynamic performance through the structural weight reduction of a strut-braced wing configuration designed for next-generation Hybrid-Electric Regional Aircraft.
This work presents the complete development and maturation process of the MTEF demonstrator, describing its evolution from conceptual design activities to manufacturing realization and preliminary functional testing. The objective is to illustrate the transition from an optimized morphing concept to a fully operational hardware demonstrator ready for experimental validation.

2. Methodology

Starting from aircraft-level aerodynamic requirements and morphing performance targets, the flap architecture was progressively defined through multidisciplinary design activities involving aerodynamic analyses, structural assessments and genetic optimization procedures aimed at identifying the optimal compliant architecture capable of achieving the required morphing shapes while satisfying structural and manufacturing constraints, -.
Following the advanced design phase, significant efforts were devoted to the development of the executive manufacturing design of the demonstrator. Several modifications were introduced with respect to the advanced design baseline to accommodate dedicated assembly requirements, improve structural integration and facilitate installation of the actuation and instrumentation systems.

The manufacturing phase represented a crucial step in the technology maturation process. A fully digital workflow was implemented, encompassing CAD modelling, kinematic assessments, CAM programming and virtual manufacturing simulations. Design-for-manufacturing activities and process validation were performed using Autodesk Fusion for Design and Manufacturing , enabling virtual verification of machining operations, assembly procedures and manufacturing feasibility prior to production.
All structural components of the demonstrator were manufactured through Computer

Numerical Control (CNC) technologies. The adopted manufacturing processes included laser cutting, CNC press-brake forming and five-axis machining operations performed on a DVF 5000 machining centre. Virtual simulations of the complete manufacturing chain were conducted before fabrication to optimize machining strategies, verify process feasibility and minimize production risks.

3. Results

The resulting demonstrator consists of a full-scale morphing trailing edge flap section specifically developed for experimental validation activities, Figure 1 and Figure 2. Following the completion of manufacturing and pre-assembly operations, a preliminary functionality assessment was performed on the actuated demonstrator prior to its final installation within the complete test-rig environment.

The demonstrator was mounted on a dedicated support structure and actuated through an external linear actuator integrated according to the executive design configuration. The actuation system was characterized by a maximum force capability of 9 kN, a maximum stroke of 150 mm and a 12 V–20 A power supply. The preliminary testing campaign focused on verifying the kinematic behaviour of the morphing mechanism, evaluating the achievable actuation excursion and assessing the resulting trailing-edge deformation and tip deflection under controlled actuation conditions.

The preliminary tests confirmed the functionality of the compliant morphing architecture and demonstrated the feasibility of the targeted morphing kinematics. The observed deformation behaviour showed consistency with the expected design response, providing confidence in the adopted design and manufacturing approach, Figure 3.

In parallel, several activities were conducted in preparation for the final experimental campaign. These included the assessment of optical fibre sensing solutions, the availability verification of LVDT displacement sensors, the definition of dedicated measurement procedures for monitoring actuation displacement and trailing-edge tip deflection, the definition of surface finishing procedures and demonstrator branding implementation, as well as the development of the video acquisition layout for future testing activities. Although the load cell, LVDTs and fibre optic sensors were already available, their installation was intentionally postponed to the subsequent experimental phase following completion of the demonstrator finishing process and final instrumentation integration.

The presented activities represent a significant step toward the experimental validation of adaptive high-lift technologies and contribute to increasing the technology readiness level of morphing wing solutions within the Clean Aviation framework.

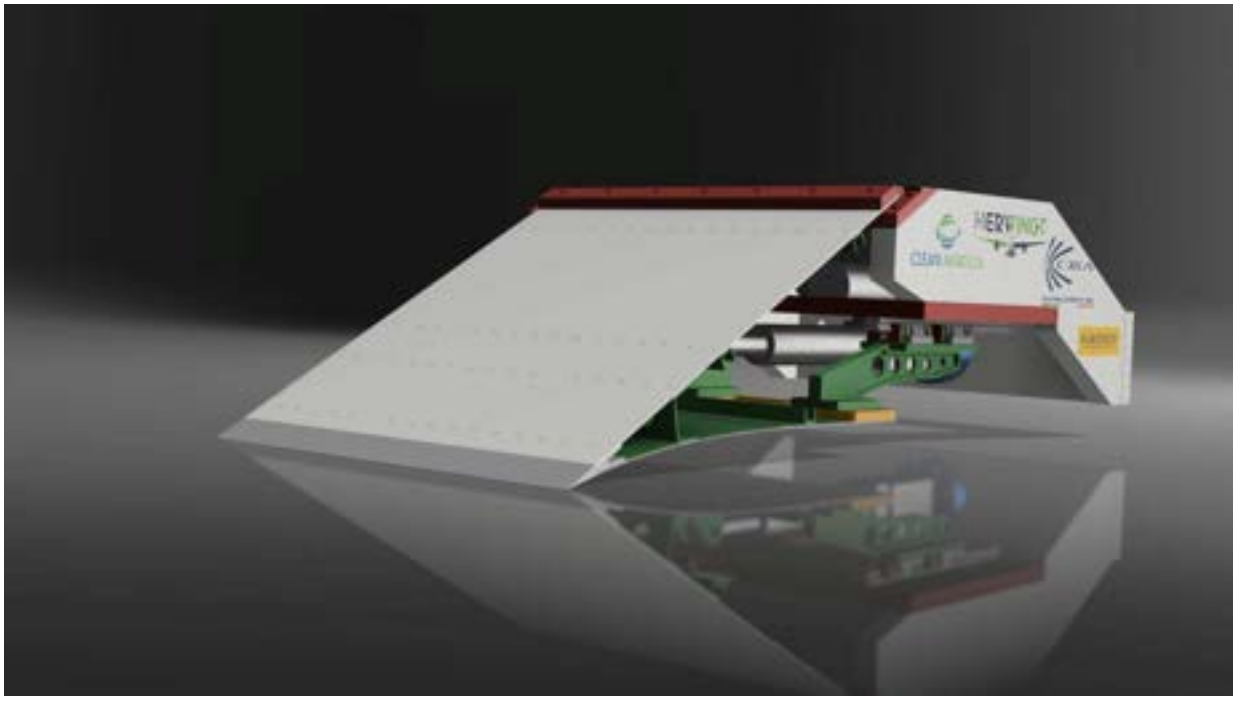


Figure 1. Executive design of the MTEF with simulation of surface finishing



Figure 2. Executive design of the experimental set-up for functional, dynamic and static tests



Figure 3. MTEF preliminary functional test under actuation (upside down position)

Acknowledgement: The HERWINGT project has received funding from the Clean Aviation Joint Undertaking under Grant Agreement No. 101102010. The Clean Aviation Joint Undertaking receives support from the European Union's Horizon Europe Research and Innovation Programme and from the Clean Aviation members. The views and opinions expressed herein are those of the authors and do not necessarily reflect those of the European Union or the Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

Experimental Geometry Reconstruction and Numerical Validation of a Full-Scale Morphing Aileron Demonstrator

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Morphing control surfaces have emerged as a promising approach for enhancing aerodynamic efficiency by enabling continuous adaptation of wing geometry to varying flight conditions. The development of such systems requires accurate experimental characterization of their deformation mechanisms and robust validation of the numerical models employed during the design process. In this context, full-field optical measurement techniques provide a valuable tool for capturing the complex kinematics of compliant morphing structures under both static and dynamic loading conditions.

This work presents the experimental investigation of a full-scale morphing aileron demonstrator developed within the HERWINGT project. The study focuses on the reconstruction of the three-dimensional deformed geometry of the morphing structure and on the validation of the corresponding numerical models through laboratory and wind tunnel testing. Initial experimental activities included quasi-static and dynamic actuation tests aimed at characterizing the response of the demonstrator across a representative range of operating conditions. Shape measurements were performed using a multi-camera optical system combined with Digital Image Correlation (DIC), enabling non-contact reconstruction of the deformation field with high spatial resolution.
Subsequently, the morphing aileron was integrated into a representative outer-wing test article and subjected to aerodynamic loading in a wind tunnel. The optical measurement setup was extended to the wind tunnel environment to capture the morphing geometries under flow conditions and to quantify the influence of aerodynamic loads on the structural response. The reconstructed geometries were compared with numerical predictions obtained from the aero-structural modelling framework adopted during the design phase. Particular attention was devoted to the assessment of deformation accuracy, spanwise and chordwise shape evolution, and dynamic behaviour of the morphing mechanism.
The results demonstrate the capability of optical full-field measurement techniques to provide detailed geometric information for large-scale morphing structures in both laboratory and aerodynamic testing environments. Furthermore, the comparison between measured and simulated configurations provides valuable insight into the predictive accuracy of the numerical models and supports their use for the analysis and design of future morphing control surfaces. The presented methodology establishes a comprehensive experimental framework for the validation of morphing-wing technologies and contributes to the advancement of reliable aero-structural modelling approaches for adaptive aircraft structures.

Experimental testing of spanwise wingbox deformation effects on the achieved morphing trailing-edge shapes of the Translation Induced Camber concept

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1. Introduction

Camber-morphing concepts have shown their capacity to reduce drag by 16–50% or 20–25% in 2D subsonic experiments. One realization of camber morphing is the Translation Induced Camber (TRIC) concept developed at TU Delft . TRIC consists of a discontinuous trailing edge with a tailored-thickness skin, which includes a cut on the pressure side that allows the skin to slide inwards and outwards to generate camber changes. TRIC demonstrated a 15%-chord delay in boundary-layer transition between morphing angles during subsonic wind-tunnel tests .
However, the above wind-tunnel as well as the existing bench tests assumed a rigid wingbox, whereas modern high-aspect-ratio wings exhibit significant elastic deformation . Therefore, the objective of this experiment is to evaluate how spanwise wingbox deformation affects the achieved morphing shapes, providing the first measurements of a phenomenon omitted in previous studies and potentially introducing a new parameter in the design of morphing systems.

2. Methodology

The TRIC morphing concept has recently been applied to a multifunctional strut whose trailing edge morphs to enhance the aerodynamic efficiency of a Strut-Braced Wing (SBW) within the framework of the HERWINGT project. In this configuration, the thickness of the morphing trailing edge was tailored , and aerodynamic analysis predicted a 1–3% drag reduction at SBW level . A recent numerical study evaluated the influence of spanwise strutbox deformation on the achieved morphing shapes. It showed that concave strutbox deflections reduce the concave morphing deflection angles by up to 2.1° while increasing the convex morphing angles by up to 1.7°, whereas convex strutbox deflections have the opposite effect.

This work aims to experimentally validate the numerical results of . The full-scale strut has a total length of 11.8 m, but only its straight portion is morphed . This morphing region is divided into five independently actuated morphing modules, each 1.6 m long. Therefore, the effect of the spanwise strutbox deformation can be measured by physically building a single morphing module and imposing on it the same curvature observed in the corresponding region of the full strut. The curvature represents the rate of local deformation along the span, and it is expected to have a stronger effect on the morphing shapes than absolute displacement.

The purpose of the experimental setup is to load the morphing module with a constant bending moment, thereby achieving a nearly constant curvature along the entire strutbox. To ensure that the section is subjected to a uniform bending moment, the strut spars were extended beyond the strutbox and connected to steel bending arms using bolts, as shown in Figure 1. An axle passes through both spars on each side, holding the specimen in position while allowing rotation about it. Rotation about the x-axis is only permitted on the left side, where the axle position is fixed, whereas on the right side translation along the *y*-axis is also allowed by placing the axle in a slotted hole. A horizontal force is then applied at the bottom of the bending arms to impose either a concave or convex deformation on the strutbox. Once the desired curvature is reached, the morphing actuators are activated, and the achieved morphing shapes are measured using DIC cameras, while the actuation loads are recorded through a load cell placed in the actuator axis.

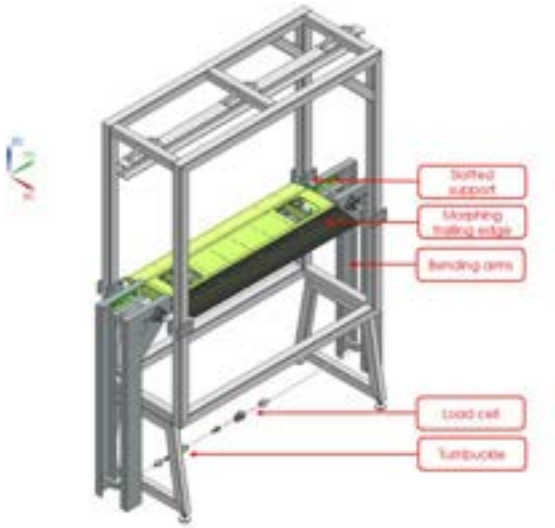


Figure 1. *CAD representation of the experimental setup*

3. Results / Conclusions

The experimental results are not yet available. The composite morphing strut has been manufactured and functionally tested, and the test setup has been successfully assembled, as shown in Figure 2. The next step is to complete the configuration of the DIC cameras, after which the experimental campaign is planned to take place in July 2026.

The main outcome of the campaign is expected to be the quantification of the effect of spanwise deformation on the achieved morphing shapes. While the numerical study has already demonstrated the influence of double curvature on the morphing behavior, the experimental investigation will provide additional insight by capturing effects that were not included in the linear numerical FE model. These include friction, potential nonlinearities, and stiffness changes in the morphing skin under high double-curvature deformation. The results are therefore expected to refine the understanding of how real structural behavior influences the performance of morphing trailing-edge systems.



Figure 2. *Photograph of the assembled experimental setup*

Sustainable Aviation Propulsion

Chaired by:
Dr. Arne Seitz (Bauhaus Luftfahrt, Germany)

Effects of Sustainable Aviation Fuel on the Performance, Emissions, and Combustion Stability of a Small Turbojet Engine

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1. Introduction

Sustainable Aviation Fuels (SAF) are considered one of the most promising pathways for reducing the environmental impact of aviation while maintaining compatibility with existing

gas turbine propulsion systems . Although SAF utilization has been extensively investigated in large commercial aircraft engines, significantly less attention has been devoted to small turbojet engines used in unmanned aerial vehicles, experimental aviation, and compact propulsion applications. In comparison with large gas turbines, small turbojet engines exhibit substantially higher sensitivity to fuel property variations due to compact combustor geometry, short residence times, and limited thermal inertia . These factors may directly influence combustion stability, flame behavior, thermal loading, and exhaust emissions. The presented work experimentally investigates the influence of SAF on the operational, emission, and combustion stability characteristics of a small turbojet engine with a nominal thrust of 200 N.

2. Methodology

The experimental investigation was performed on a laboratory test stand equipped with a small turbojet engine with a nominal thrust of 200 N. The test setup included measurement systems for fuel consumption, rotational speed, exhaust gas temperature, and pressures. Comparative measurements were conducted using conventional Jet-A1 fuel and neat SAF under steady-state and transient operating conditions covering the complete operating range from idle to maximum thrust. Performance measurements focused on thrust characteristics, engine acceleration response, rotational speed stability, and thermal response during different operating regimes. Fuel consumption was monitored to evaluate the influence of SAF on engine operational efficiency. Simultaneously, exhaust gas analysis was carried out to quantify the concentration of major gaseous emissions, including carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and unburned hydrocarbons (UHC).

Particular attention was devoted to combustion stability assessment. Small turbojet engines are characterized by very compact combustion chambers and high rotational speeds, making them considerably more sensitive to fuel property changes than large aviation gas turbines. Therefore, transient throttle changes and rapid acceleration regimes were included in the experimental campaign to identify potential combustion instabilities, flame fluctuations, exhaust temperature oscillations, and variations in rotational speed behavior associated with SAF utilization.

The experimental data obtained during the measurements were subsequently compared to identify differences between conventional and sustainable fuels with respect to engine performance, combustion behavior, and environmental impact. The study further evaluates the operational consequences of SAF implementation in small-scale propulsion systems and discusses the influence of fuel properties on combustion quality and engine reliability.

3. Results

The experimental results demonstrate that SAF fuel utilization in a small turbojet engine produces measurable differences in combustion behavior and emission characteristics compared with conventional Jet-A1 fuel. While the overall engine performance remained comparable, variations in exhaust gas temperature distribution, transient response, and rotational speed stability were observed during selected operating regimes. The measurements revealed noticeable differences in ultrafine particle formation between the tested fuels, particularly at medium and high rotational speeds, as shown in Figure 1. In addition, SAF operation resulted in consistently lower carbon monoxide emissions across the investigated operating range (Figure 2).

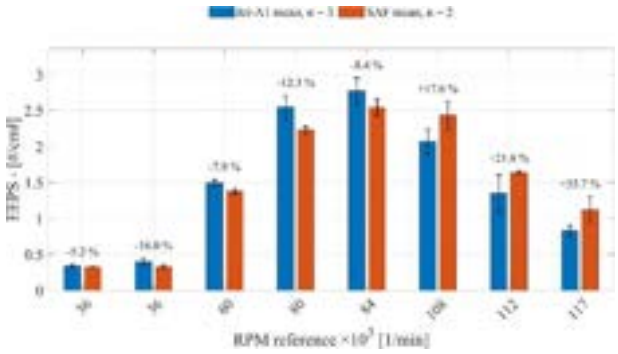


Figure 1. *EEPS ultrafine particle concentration for Jet-A1 and SAF fuels at different engine operating regimes*

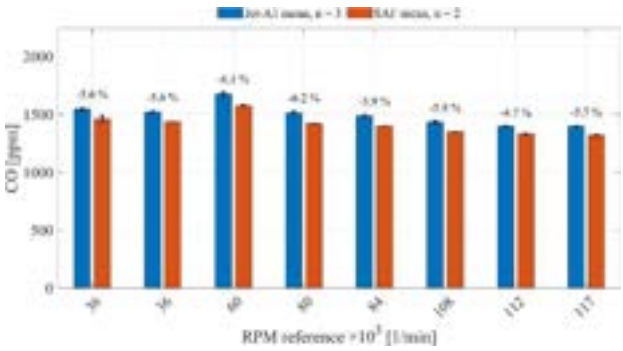


Figure 2. CO *emissions* of the small turbojet engine fueled with Jet-A1 and SAF at different engine speed references.

The measurements further indicate that small turbojet engines exhibit increased sensitivity to fuel composition changes, particularly during transient operating conditions where combustion stability becomes critical. The use of SAF resulted in changes in gaseous emissions and particulate matter formation, confirming the influence of fuel properties on combustion efficiency and flame stabilization. The results obtained contribute to the understanding of SAF applicability in compact aerospace propulsion systems and support further development of low-emission small gas turbine technologies.

Design of Hydrogen-Based Propulsion Systems and Implications for Regional Aircraft Operational Safety

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1. Introduction

As hydrogen evolved to the focal point of aviation research to decarbonize its sector in the coming decades, the detailed design of hydrogen-based propulsion systems including their implications on the operational safety of respective aircraft and their interaction becomes increasingly important. Despite the challenges bound to the integration of liquid hydrogen (LH_2) systems – required by the low energy density of gaseous hydrogen – at least equivalent level of safety compared to conventional systems must be maintained for feasible solutions. The presented study delves into the layout and detailed safety assessment of multiple propulsion system options for fan and propeller driven aircraft, thereby setting the basis for objective evaluations of various upcoming architectures.

2. Methodology

The presented studies are based on the Dornier D328 reference aircraft, as its unique CS-25 certification for both turbofan and turboprop propulsion systems serves as a superior baseline for the comparative assessment of multiple powertrain architectures. The aircraft-bound storage of cryogenic LH_2 comes with a specific set of challenges, especially concerning the degradation of material performance, volatility of the gas, its boil-off management, and flammability, amongst other factors. An aft-fuselage integration of the LH_2 tanks is considered for the 32-passenger aircraft, as the rear cargo hold of the legacy aircraft facilitates its integration.

As few recent aircraft design studies analyze the safety implications of LH_2 systems in general, but also with respect to the specifics of the propulsion system in the required level of detail and on a systematic basis, this study is based on a system-and-powerplant-focused certification gap analysis, which is amended for the configuration under investigation. Following the layout of required assumptions and boundary conditions as well as the methodological foundation, an overview of the considered powertrains is given. The conventional turbofan and turboprop architectures are introduced as reference, followed by a detailed description of the hydrogen variants. Specifically, these include a hydrogen-combusting turbofan powertrain as well as propeller-driven variants based on fuel-cell-electric and hybrid systems.

Subsequently, safety considerations through conscious architecture design as well as through a fault-propagation assessment are examined. For this a simplified failure case depiction is used to evaluate all relevant failure scenarios resulting in loss of one or more propulsors to assess the fulfilment of basic performance and controllability requirements. Failure budgets are allocated and their resulting criticality for the overall systems discussed. The considerations are driven by the base assumption that various propulsion systems need different subsystems, for which the authors expect individual criticalities. Therefore, after the global investigation of the gap-analysis-optimized architectures the respective cases are evaluated and compared against each other and the reference systems.

3. Conclusions

These studies emphasize the different boundary conditions placed on the design of safe hydrogen propulsion systems for future aircraft and serve as a basis for deeper safety analyses according to the selected propulsion system. The anticipated results will provide a comparative analysis of the safety profiles for hydrogen-combusting, fuel-cell-electric, and selected hybrid architectures. By evaluating the allocated failure budgets, together with new, hydrogen induced, top level aircraft effects, the study will identify specific subsystem criticalities induced by each energy conversion strategy. It is expected that the findings will demonstrate the feasibility of achieving CS-25 safety levels for LH_2-powered regional aircraft through targeted architectural modifications. These conclusions will offer a systematic basis for future design decisions, bridging the gap between conceptual studies and safety engineering. At last, the work establishes a basis for evaluating and mitigating risks in hydrogen-driven aircraft propulsion systems.

Acknowledgment: The projects, on which the work of this article is based, were funded by the German Federal Ministry for Economic Affairs and Climate Action under grant numbers 20M2246C (DOXWING) and 20M2109H (328H2-FC) as well as by the European Union, under

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The effect of a hydrogen flame on the geometric structure and tightness of contacting surfaces

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1. Introduction / Objectives

The advantage of using hydrogen fuel is its high calorific value and environmental friendliness. The product of hydrogen combustion in the presence of oxygen is water without greenhouse gases, pollutants, and particulate matter. However, it is a light gas and can easily escape from both tanks where it is stored under high pressure and fuel systems. Unfortunately, it is prone to explosions and has high ability to penetrate metals due to the small size of its molecules. Therefore, it is essential to test the surface roughness of hydrogen fuel system's elements. Roughness influences engine performance by causing earlier boundary layer transition. In turbines it strengthens convective heat transfer . Hydrogen influences intensity and velocity of turbulence within the furnace chamber. There is little published information on the effect of hydrogen on the surface roughness. Consequently, studies were conducted on surface roughness of selected components of the hydrogen fuel system.

2. Methodology

To investigate the effect of hydrogen fuel on the surface condition of selected components of a hydrogen fuel system, surface texture tests were conducted on them. A test rig was designed in which selected, interacting structural components of the fuel system were placed. They were pressed together along the contact surface and exposed to a hydrogen flame. Selected sections of the contact surface were tested for roughness both before and after exposure to a hydrogen flame. Both contact and optical texture measurement instruments were used for the measurements.
The methodology for processing surface topography measurement data included the following main steps: (1) removal of distortions at the edges of the measured surfaces, (2) identification of analysis areas, (3) filtering of the base surface shape profile and filtering of the waviness and roughness profiles, (4) removal of outliers from the data that clearly deviate from the rest, (5) calculation of selected surface roughness parameters, (6) given that the tightness of the connection is influenced, among other things, by the uniformity of the distribution of surface elevations—determination of the cutoff level for elevations and islands, (7) preparation of topographic maps for determining the parameters of surface elevations and deep depressions through the segmentation of elevations and deep depressions (8) calculation of selected surface texture parameters with special attention paid to functional parameters -- the effective surface area, the liquid retention index of the core, and the liquid retention index of the voids.
The measured values were subjected to statistical tests, which allowed for the verification of the statistical hypotheses. Descriptive statistics and correlation coefficients for the measured surface features were determined. Since the measured values can distort the results of surface model estimation, an analysis of outliers, influential observations, was conducted

using Cook's distance. With regard to the derived regression equations, the coefficients of determination and confidence intervals for the estimated coefficients were also calculated. Following the analysis of the results, the surface texture parameters with the greatest influence on the uniformity of the distribution of ordinates contributing to the tightness of the surface joint at the interface were identified.

3. Results / Conclusions

The microgeometry of the contact surfaces of the hydrogen fuel system components used in the study, prior to their exposure to a hydrogen flame, varied in directions correlated with the kinematics of the cutting tool's motion relative to the component being machined. Deformation processes at the macro- and micro-scales of the contacting surfaces subjected to hydrogen flame occurred with varying intensity, depending on the distance of the tested areas from the hydrogen flame and components' stiffness. The tightness of the joint depends on the fit of the contacting surfaces at the macro scale — the fit of the shape and dimensions of the average surfaces — and at the micro scale. The susceptibility of the contacting surfaces to mechanical and thermal loads also plays a significant role. Useful parameters when describing surfaces in terms of joint tightness are amplitudinal, spatial, and especially functional texture parameters of the contacting surfaces.

Safety-Assured Performance Assessment and Uncertainty Quantification of a Hydrogen-Fuelled Aircraft Engine Using a Surrogate Model

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1. Introduction / Objectives

The ongoing growth of aviation has a significant impact on the environment. Specifically, the sector is responsible for 4% of global warming . Consequently, research is focusing on more environmentally friendly aviation fuels, such as SAFs and hydrogen, to mitigate this footprint. Although there are several publications on the usage of hydrogen on aircraft engines, there is a limited number of studies on safety and reliability risks related to hydrogen-fuelled propulsion. In addition, a data-driven model can boost the uncertainty quantification analysis by allowing fast calculations of large samples at a fraction of time. The overall goal is to ensure engine safety and to acquire a more robust performance estimation that could potentially facilitate complete uncertainty propagation across all aircraft-level components.

2. Methodology

To achieve the above objectives, a physical model of a two-shaft turboprop engine is initially developed using commercial software . The engine is designed through a multi-point design analysis (RTO, MCL, MCR) and its performance is assessed across the entire operating range. Same design sizing procedure and performance estimation for both fuel engine models

across the complete flight envelope. A custom-made hydrogen fuel map is used with parahydrogen properties. After the physical model development, a surrogate model is developed. The latter is a simple artificial neural network (ANN), featuring a ResNet-style with skip connections, and consists of 15 models with different initialization seeds to increase the robustness of the performance predictions. Subsequently, an uncertainty quantification methodology is implemented to increase engine safety, as illustrated in Figure 1. Concretely, all possible aircraft engine uncertainty sources, such as component efficiency shortfall, manufacturing tolerances and SAF LHV/fuel injection temperature (depending on the fuel), are propagated to the output performance parameters though a Monte Carlo simulation using a Latin Hypercube Sampling (LHS) . Each source of uncertainty is evaluated independently, estimating the respective TET margins for each corresponding source. The calculated TET margins are then combined through a simple stack-up and deducted from the maximum TET value, resulting in the final robust design. Additionally, a detailed analysis that distinguishes the aleatoric and the epistemic uncertainties from the surrogate mode was implemented. Once the engine's safety has been secured, even under the worst-case engine design, the same uncertainty quantification approach is applied to quantify the uncertainties of the key engine performance metrics. The surrogate model results are validated against those of the physical model for both fuels to investigate the accuracy of surrogate model's performance predictions. Finally, the results of the performance evaluation resulting from the uncertainty quantification for both fuels are presented and compared with each other.

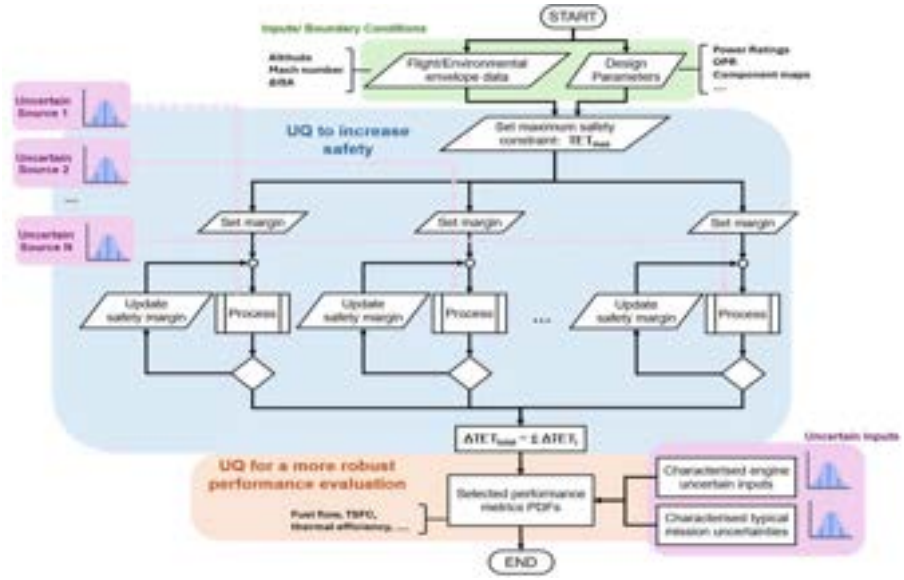


Figure 1. *Variation of the proposed UQ implementation methodology for the aircraft engine performance case, featuring a TET margin stack-up.*

3. Results / Conclusions

Every surrogate model can accurately predict engine performance in relation to the physical model. For instance, the mean absolute error for TET is around 1.5 K to 2.0 K, while a maximum error of 7.5 K is observed in the worst-case engine design. Additionally, it is noted

that the distribution of uncertainty source has a significant impact on mean TET value. Especially, component design shortfall results in 15 K higher mean TET than the rated TET due to triangular distributions. In contrast, manufacturing tolerances, fuel LHV and fuel injection temperature estimate mean TET close to the rated TET due to the input normal distributions. Furthermore, total aleatoric TET margins between the physical and the surrogate baseline engine model are identical at 55 K, while there is an improvement by 6 K in hydrogen physical model. Consequently, hydrogen engine performance is improved not only using the fuel itself, but also because it enables higher designed TET.

Uncertainty Quantification of the Energy Supply for Low-Carbon Aviation

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1. Introduction / Objectives

The transition toward low-carbon aviation requires the introduction of alternative energy carriers capable of replacing conventional fossil-based fuels while maintaining acceptable performance, cost, and operational constraints. Among the most promising candidates are liquid hydrogen, synthetic fuels (e-fuels), and battery-based electric propulsion systems. However, comparing these solutions remains challenging due to the strong coupling between aircraft design, propulsion architecture, and energy supply chains, as well as significant technological uncertainties.
This work proposes an integrated and uncertainty-aware framework for the comparative evaluation of alternative aviation energy carriers across multiple aircraft categories, ranging from commuter to long-haul configurations. The proposed approach combines tank-to-wake (TTW) aircraft performance modeling with well-to-tank (WTT) energy supply chain analysis to provide a comprehensive system-level assessment of future low-carbon aviation concepts.

2. Methodology

The proposed framework evaluates the performance of alternative aviation energy carriers by integrating aircraft-level and energy supply chain analyses under uncertainty. The study considers three main energy pathways:

- synthetic fuels or “e-kerosene” based on Direct Air Carbon Capture
- liquid hydrogen from water electrolysis
- Direct electricity use and storage

The comparison considers four aircraft categories ranging from commuter aircraft to long-haul transport configurations. For each category, four propulsion technologies are investigated: conventional airplane (combustion of kerosene), hydrogen fuel cell systems with electric propulsion, hydrogen combustion in gas turbine (turbofan or turbo-propeller), and batteries with electric powertrain.
The methodology is structured into four main steps. First, a comprehensive bibliographic review is conducted to identify, select, and harmonize the key parameters required for both aircraft performance modeling and energy supply chain assessment. Particular attention is given to ensuring consistency across literature sources and to defining realistic ranges of

variation for uncertainty propagation.
Second, a tank-to-wake (TTW) analysis is performed using a parametric aircraft design framework based on the Generic Airplane Model (GAM). This modeling environment enables the estimation of aircraft mass breakdown and mission energy consumption as a function of a limited set of technological and design parameters. The approach allows consistent comparisons between conventional and unconventional propulsion architectures.
Third, a well-to-tank (WTT) analysis is developed to quantify the energy requirements associated with the production, conversion, and distribution of each energy carrier. The framework includes assumptions related to electricity generation, hydrogen production through electrolysis, liquefaction processes, and synthetic fuel production pathways such as Fischer–Tropsch synthesis. This step extends the analysis from onboard aircraft performance to the complete energy pathway.
Finally, uncertainty propagation is implemented using Monte Carlo simulations. Uncertain variables are divided into two categories: **technology specific parameters** : fuel cell efficiency, power density, battery specific energy, and hydrogen storage characteristics, etc. **design-related parameters** : mass estimation coefficients, propeller or fan efficiency and lift-to-drag ratio variation.

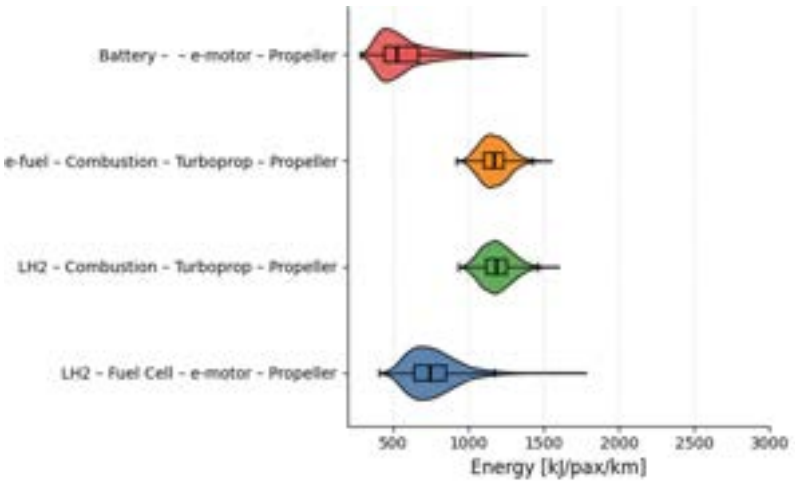


Figure 1. *Tank-to-wake energy consumption of commuter airplane per passenger-kilometer for different energy carriers.*

3. Results / Conclusions

Preliminary results highlights overlaps between competing technological solutions (Figure 1) in the Tank-To-Wake scope. Hydrogen fuel-cell systems generally exhibit higher variability in energy consumption per passenger and per distance compared to hydrogen combustion configurations or synthetic kerosene. Battery-electric solutions are competitive for very short-range applications but remain highly sensitive to technological assumptions.
Overall, the results indicate that the relative performance of alternative energy carriers strongly depends on aircraft design assumptions. No single solution emerges as universally optimal across all aircraft categories. The proposed framework provides a systematic

approach for assessing future low-carbon aviation technologies while explicitly accounting for uncertainty and variability in technological development.

Priority goal decomposition for multi-level assessment of the conceptual aircraft exposure and impact on environment

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[2] National University "Kyiv Aviation Institute", Ukraine

[3] Noise ACH, Poland

1. Introduction / Objectives

The transition from fossil to decarbonized fuels is the central point of the transformation within the global aviation sector at present. Hydrogen plays a very important role in the decarbonization of the sustainable aviation fuels and in-flight energy consumption. Its implementation is considered in two ways - direct fueling of aircraft engines and hybrid electric propulsion (HEP) with electricity charging of the electric engine from hydrogen fuel cells . Both concepts are revolutionary technologies for aviation sector , considered by EFACA project, which need for tremendous modelling to confirm their efficiency for ICAO standard requirements (noise, local air quality LAQ and CO_2 emission), exposure in the vicinity of airports (to confirm the ACARE environmental goals) and at global fleet level (to confirm the ICAO long-term aspirational goal – ICAO LTAG) . The ICAO LTAG considers the assessment of global aviation carbon footprint assessment defined for CO2 and other greenhouse gas (GHG) emissions (methane, nitrogen oxides, water vapour, particles, etc) and effects (contrails and ozone) influencing the radiative forcing from aviation. A principal value for that is the GHG and LAQ emission factors along the total flight of the aircraft, which are changed depending on flight (and engine operation) mode and outside conditions.

2. Methodology

LAQ and GHG emission factors are assessed using the certification data for emission indices of the aircraft engines via their recalculation for the flight mode conditions by methods proposed in ICAO Doc 9889. For the LAQ efficiency of the new aircraft design the ICAO Annex 16 standard requirements are limited by the Landing-Take-Off (LTO) cycle. For the CO2 emission assessment of the new aircraft design the ICAO standard requirements consider the total flight profile in accordance with Top Level Aircraft Requirement (TLAR) to this baseline design. Both metrics are compared to similar values for a reference aircraft – usually the best in the class of aircraft to which the new concept aircraft belongs. It is a vehicle level of the assessment of the environmental efficiency of the baseline aircraft. Aviation noise in this decomposition should also be considered as an independent strategic criterion of the environmental performance of the conceptual hydrogen aircraft, combining design solutions at the aircraft level with the actual spatial exposure of the population in the vicinity of airports. The regulatory basis for such an assessment remains the requirements of ICAO Annex 16, Volume I "Aircraft Noise", however, the modern development of these requirements shows a transition from a purely certification logic to a broader analysis of technological and operational trade-offs. In particular, within the framework of CAEP/13, new approaches to noise certification for emerging technology aircraft, supersonic and

subsonic aeroplanes were considered, including the proposed provisions of Chapters 13, 15 and 16 of Annex 16 Volume I.

3. Results & Conclusions

At the airport level of assessment the LAQ modelling for the air traffic scenario is provided – for the reference and baseline fleets in operation, where the emission factors for them are used in accordance with findings implemented at vehicle level . Besides the aircraft the several mobile and stationary sources of emission are required by ICAO Doc 9889 to be considered for the inventory analysis and air pollution modelling using the dispersion models. The calculated concentrations for airport traffic scenario are compared with the standard limits for matters under the consideration, the nitrogen oxides and particles are of the main concern among them. If the isopleth is found for the standard limit, it defines the area of airport LAQ influence or airport LAQ footprint. Comparison between the airport LAQ footprint for the baseline and reference fleets may show the efficiency of the new technology at airport level. At this level of assessment it is also important to show the efficiency of new emission reduction technologies by comparisons between the LAQ influence areas (aircraft LTO LAQ footprints) of the single LTO cycles of baseline and reference aircraft – it is more informative about air pollution exposure of both aircraft designs than the comparison of their LTO emission data due to ICAO Annex 16 requirements.
The priority goal decomposition of carbon footprint from global aviation till the ICAO Annex 16 LAQ and CO2 emission requirements – through the airport and LTO LAQ footprints is discussed showing their fundamental dependence from emission factor, which is a subject of technology and operational reduction. At the same time, the results of the integrated dual stringency analysis for CO_2 and noise confirms that these two areas of environmental performance cannot be reduced to a single indicator, since they have different spatial scales of impact, time exposure, mitigation mechanisms and regulatory frameworks. Therefore, noise assessment should form a specific multi-level line of analysis: from aircraft certification indicators and noise characteristics of individual LTO operations to noise exposure contours around airports and fleet renewal scenarios.

Smart Materials & Structures

Chaired by:
Prof. Patrizia Lamberti (University of Salerno, Italy)

Nanodiamond-based coating for aircraft transparencies: Test equipment and measurement program

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1. Introduction / Objectives

Cockpit windows are subject to abrasion by atmospheric agents and cleaning procedures. Abrasion considerably increases the level of haze of the transparencies, which, in turn, deteriorates the visual perception of the outer scenario by the pilot, particularly for plastic transparencies. In the NaBuCo project, the use of nanodiamond-based coating to increase

abrasion resistance of acrylic cockpit windows is investigated. Beyond this main goal, the nanodiamant coating is required not to negatively affect the mechanical and optical quality of the transparencies. To ensure the fulfillment of this requirement as well as of the main goal, an extensive test program is necessary. Within NaBuCo, TU Dresden is in charge of providing proper equipment for such test program and performing the tests. This contribution provides an overview of this task, including the development of a novel approach to the measurement of optical distortions, and presents a selection of the test results.

2. Methodology

The NaBuCo measurement program includes several test benches:

- a tensile testing machine with climatic camber
- an innovative test apparatus for the measurement of optical distortions
- a test bench for the measurement of crazing resistance according to MIL-PRF-8184
- a measurement system for the determination of luminous transmittance and haze according to ASTM D 1003
- a "falling sand tester" for the simulation of abrasion load according to ASTM D 968
- a "oscillating sand tester" for the simulation of abrasion load according to ASTM F 735.

The tensile testing machine is mainly used to determinate a possible deterioration of the mechanical properties (Young modulus as well as static and cyclic strength) at different temperatures due to the nanodiamond coating. Besides this, it is used to test the adhesion of the coating under large strain of the material.
The optical distortion test bench (see Fig. 1) is based on a novel principle (adaptation of the digital image correlation method used for the determination of mechanical displacement and strain fields) and allows for measuring optical distortions with high precision and resolution.

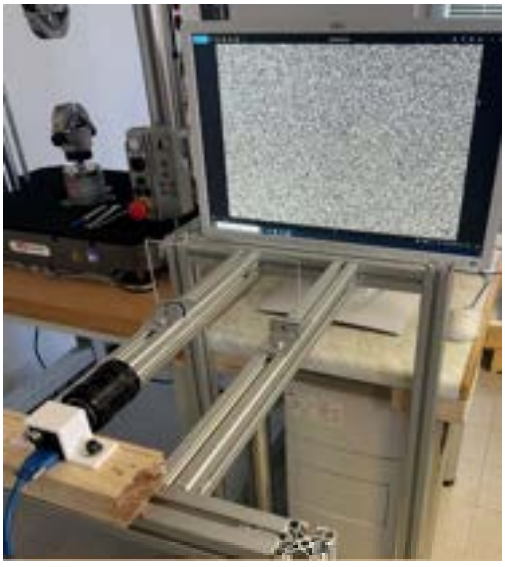


Figure 1. *The optical distortion test bench.*

The crazing test bench is used to determine the level of stress at which the cockpit material, after chemical loading by solvents like isopropyl alcohol or ethylene glycol, begins to craze (to develop a network of hair-line cracks).
The two test setups to reproduce abrasion loads are used to determine the resistance of the coating to abrasion as well as the performance of the coating in protecting the transparency from deterioration due to abrasion. The transmittance and haze measurements are finally used to quantify the effect of the abrasion load on the transparency.

3. Results / Conclusions

Selected results of the measurement program are presented. Special focus is given to the results obtained by the distortion test bench, due to its novelty and its potential for further developments. Besides this, results obtained by the other components of the measurement system are presented, which give insight into the performance of the developed nanodiamond coating.

Surrogate model for lightweight metamaterial sandwich optimization

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1. Introduction

With the rapid development in composite optimization of aerospace structures came a burden of thin structures, which are more prone to failure by buckling than to the stress and strain failure modes. This leads to a revival of the use of sandwich structures in primary load-bearing structures of an aircraft. A number of authors in the field have already employed the lightweight core in their design optimization process. Nevertheless, optimization by varying the geometry of sandwich cores remains a largely unexplored possibility.
Due to the rapid progress in mechanical metamaterial design and additive manufacturing technologies, past technological limitations are no longer an issue. Currently, the most apparent obstacle is the lack of reliable models of the behavior of the new materials. The presented study focuses on the creation of a parametric model of homogenized properties of a metamaterial sandwich core, which could be employed alongside the current frameworks for composite optimization.

2. Methodology

The authors propose a novel approach to the homogenization of the sandwich core properties with the use of a surrogate model obtained by Bayesian optimization. The approach will be tested on the 2D metamaterial core structure shown in Figure 1, which was designed by the authors to overcome some of the issues associated with the use of the traditional honeycomb core.
Surrogate model of the homogenized core properties is created based on virtual experiments conducted on Finite Element models of the sandwich structure, which are automatically generated using an in-house meshing software. Core thickness and cell angle are used as optimized variables, and sample sandwich panels with different values of these

variables are selected from the predefined design space to serve as a base data for the surrogate modeling. To lessen the necessary computational effort, the sample selection is done with the use of the Bayesian approach based on the predicted impact of the sample evaluation on the precision of the created surrogate model.
To verify the precision of the completed surrogate model and the benefits arising from the use of the Bayesian approach, the completed surrogate model is validated against FE samples evenly distributed across the design space.

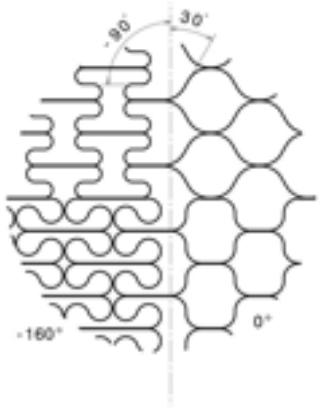


Figure 1. *Top view of the core structure with different cell angles.*

3. Results / Conclusions

Preliminary results suggest that the implementation of the Bayesian approach will significantly lessen the overall computational cost of creating the surrogate model while maintaining most of its precision. The approach can be easily repeated for other metamaterial core structures, lowering the computational cost of their homogenization and implementation into the optimization process. The authors aim to utilize the surrogate model to assess the benefits of use of metamaterial panel optimization in an aeroelastic tailoring of aircraft wing; nevertheless, the nature of the model does not limit its use to this sole application.

Through-thickness thermal response of in-situ consolidation CF/LM-PAEK manufactured by pulsed flashlamp automated fiber placement

E. Tobin, D. M. J. Peeters
TU Delft, Netherlands

1. Introduction

Out-of-autoclave (OoA) manufacturing has gained significant interest as a composite manufacturing method within the aerospace industry to meet the high production rates required by industry. Fiber reinforced thermoplastic composites, therefore, play an integral role in the future of aviation, as they offer the potential for in-situ consolidation (ISC) manufacturing. One such method of ISC is automated fiber placement (AFP), in which the material is heated by an external heat source. While the use of hot-gas and laser heat

sources is well documented as ISC heat sources, the use of a xenon pulsed flashlamp requires further research.
Xenon pulsed flashlamp heating has improved safety compared to a laser heat source while also allowing greater control than a hot-gas torch; however, the effects of different processing parameters are not well understood to date. As such, this paper aims to compare the effects of parameter variations (pulse width and pulse frequency) on the thermal history of the laminate during manufacturing, while also studying the void content, crystallinity, and interlaminar bond strength of flashlamp AFP manufactured laminates.

2. Methodology

The AFP system used for this work comprises of an AFP-XPS (AddComposites Oy), which is attached to a Kuka KR210 robotic arm. A 6kW Excelitas Humm3TM flashlamp (Figure 1) is used as the heat source. There are three flashlamp parameters that can influence power during manufacturing, and therefore, the temperature: 1) voltage, 2) pulse width, and 3) pulse frequency. However, parameters were selected such that the total lamp power remained constant. The pulse width and pulse frequency were varied so that the overall irradiation time (time the lamp is on) remained constant. Laminates were manufactured using a carbon fiber reinforced LM-PAEK material supplied by Toray Industries (Toray Cetex ® TC1225). During the manufacturing process, the placement rate and compaction force remained constant at 45 mm/s and 400 N, respectively.
Thermocouples are utilized to study the effect of flashlamp parameters on the thermal response of laminates during manufacturing. This is done by embedding five thermocouples into a [0°]10 laminate during the manufacturing process. As such, it is possible to correlate heating rates and maximum temperatures associated with different pulse parameters, while also measuring the heat affected zone (HAZ) of flashlamp heat sources.
Additional specimens are manufactured and tested in accordance with ASTM D2344 using a Zwick 10 kN Universal Test Machine. To analyze the specimen microstructure (i.e., void content), microscopy was conducted using a Keyence VK-1000 confocal microscope. Digital scanning calorimetry (DSC) was conducted to compare the degree of crystallinity of the specimens after manufacturing.



Figure 1. *Excelitas Humm3 pulsed flashlamp*

3. Results / Conclusions

Initial findings indicate that while the lamp power and total irradiation time are constant, the temperatures achieved during manufacturing differ due to the pulse width to pulse frequency ratio. In addition, flashlamp heating produces a larger HAZ than laser AFP, with

heat propagating deeper into the substrate. As such, substrate layers benefit from multiple heating and consolidation passes, as the substrate is repeatedly above the matrix glass transition temperature.

The final paper will show the effect of these differing temperature profiles on the matrix microstructure (void content and degree of crystallinity) and correlate these observations with interlaminar bond strength. It is hypothesized that the laminate void content is lower and the degree of crystallinity may be higher than with a laser heat source due to a combination of the lower cooling rate and the higher temperature measured a few layers into the substrate, as observed in initial trials [5]. Initial results indicate that laminates may not require post-processing to achieve sufficient bond strength. These findings may, in turn, also bring ISC and OoA manufacturing of thermoplastics a step closer to their adoption in the aviation industry.

Modelling the Economic Cost of a Supply Shock on Key Aerospace Materials

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[2]Politecnico di Milano, Italy

1. Introduction / Objectives

The current backlog for commercial aircraft has reached a new high of 16.000 aircraft in 2025. Although airframers would be able to scale up production the highly fragmented and diversified supply chain makes this more complicated. Labour and especially **material shortages** are often cited as the main reasons for why this is not possible. Making matters worse, many critical raw materials (CRMs) used in aircraft manufacturing originate from politically unstable regions. We model economic damages that could be caused by delayed aircraft deliveries following a potential supply shock on nickel and titanium alloys.

2. Methodology and Assumptions

To first narrow down a set of aerospace-specific CRMs we use the life-cycle inventory following Rahn et al. (2025) and the EU criticality values from literature (European Commission, 2023) as well as the GeoPolRisk method (Saldivar et al., 2025) for validation. The EU methodology constructs a matrix out of two values, supply risk and economic importance. Supply risk (SR) score gets calculated based on production concentration using the Herfindahl-Hirschmann-Index (HHI_{WGI-t}), combined with the World Governance Indicator to flag markets with poor governance. Import reliance ($\frac{IR}{2}$) depicts the share of importance of the observed material while EoL_{RIR} and SI_{SR} take into account the recycling rate and availability of potential substitutes for the material.

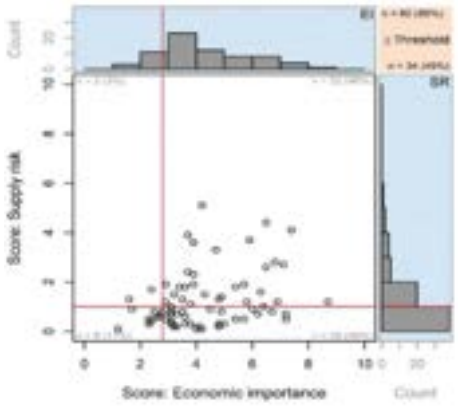


Figure 1: EU criticality matrix

$$SR = \left[(HHI_{WGI-t})_{GS} * \frac{IR}{2} + (HHI_{WGI-t})_{EUsourcing}\left(1 - \frac{IR}{2}\right)\right] * (1 - EoL_{RIR}) * SI_{SR} \quad (1)$$

Economic importance (EI) is based on the share of a given raw material in a particular sector/application A_s, multiplied by the (added) value of this activity Q_s. In the 2023 version, economic importance has been expanded upon with the addition of a substitutability index SI_{EI} which depicts the substitutability of the raw material in the given sector, depending on cost and performance.

$$EI = \sum_s (A_s * Q_s) * SI_{EI} \quad (2)$$

The GeoPolRisk method can be seen as a simplified version of the supply risk formula, only taking into account production concentration and governance score of the economic entity. While simpler, the GeoPolRisk method is much more accessible thanks to lower data requirements and its open source geopolrisk-py package. After cross-checking CRM scores and alloys from Rahn et al. 2025, titanium and vanadium stand out. Nickel alloys (Inconel 100,625,718) include titanium or vanadium as alloying elements, other alloys (Ti-6Al-4V) rely on titanium as a base metal. Thanks to their unique properties, *namely* ductility, heat and corrosion resistance, both materials are used in the propulsion system as well as for various structural elements. Based on this initial finding, we have modelled a supply shock originating from a policy shift that sanctions, among others, Russian mining company VSMPO-AVISMA. In 2022, Airbus received half of its titanium forgings from VSMPO-AVISMA while Boeing received around a third (Hepher, 2022). Taking into account glider production and continued deliveries of stockpiled parts for six months after the supply shock, we model the added operational and maintenance costs for the airlines affected by the delayed deliveries. We expand by taking into account environmental costs (3) caused by delayed fuel efficiency, which we calculate in the last step of our analysis.

$$Environmental\ Damage\ Costs = \underbrace{(Efficiency\ Loss\ Rate\ x\ Operation\ Duration)}_{Delayed\ Fuel\ Efficiency}\ x\ Emission\ Pricing \quad (3)$$

3. Results and Conclusions

Table 1: Criticality scores of a set of aerospace-specific CRMs

Table 1: Criticality scores of a set of aerospace-specific CRMs

	Titanium (Ti)	**Vanadium (V)**	Nickel (Ni)	Cobalt (Co)	Gallium (Ga)
SR_{2020} score (lit.)	1.3	1.7	0.5	2.5	1.3
SR_{2023} score (lit.)	1.6	2.3	0.5	2.8	3.9
EI_{2023} score (lit.)	6.3	3.9	5.7	6.8	3.7
$GeoPolRisk_{2022}$ (geopolrisk-py)	**0.09**	**0.18**	0.14	0.15	-

SR criticality threshold: ≥ 1.0; EI criticality threshold: ≥ 2.8; GeoPolRisk score scale: 0 (no risk) to 1 (high risk)

Table 1 shows the criticality scores for a set of aerospace-specific CRMs, both from literature and our own calculations using geopolrisk-py (economic entity: EU, year: 2022). Initial results for the supply shock on Russian titanium forgings indicate that the environmental damage costs caused by delayed fuel efficiency alone amount to €56.9 million, not yet discounted and excluding maintenance costs. Glider production during the shock leads to a brief spike in deliveries over the current rate once new sources of supply have been established. Since the start of the war in 2022 airframers are urged to diversify supply and cut ties with Russian suppliers. Our research shows the economic damage caused by a supply shock on titanium alloys, given current trade relations. The scale of the costs indicates that airframers are taking a significant financial risk by continuing to source from Russia. On the other hand, the substantial operational and environmental costs of a potential supply disruption could also explain why critical materials such as titanium and vanadium have so far been exempt from sanctions. Although our results suggest reasons why policymakers are reluctant to sanction CRM imports, it is crucial that they continue to encourage airframe manufacturers to diversify and secure their supply chains.

Analytic Modelling of the Effective Mechanical Properties of Origami Sandwich Structures

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RWTH Aachen University, Germany

1. Introduction / Objectives

Sandwich structures with a folded core have a number of advantages when compared to "traditional" sandwich structures (e.g. honeycomb, foam core): They allow for a greater design freedom through changes to the folding pattern, easier manufacture and they enable multi-functionality through secondary functions (e.g. fluid flow or routing of electrical conduit). However, these benefits are balanced by an increase in modelling complexity. This is a known problem and usually dealt with by using approaches driven by Finite-Element-Analysis (FEA) for modelling e.g. the effective mechanical properties. To solve this problem, increase modelling efficiency and enable fast Multidisciplinary Design Optimisation (MDO), this paper presents an analytic model for deriving the effective mechanical properties of a folded sandwich core, enabling efficient optimisation by variation of geometric parameters.

2. Methodology

The method used in this paper is based on the approach of Bühring et al. to describe the effective mechanical properties of lattice structures. First, a unit cell of the folded core structure is identified and modelled as a truss structure consisting of nodes connected by bars using the bar-and-hinge-model for origami structures as presented by Schenk and Guest. Using this model, the global stiffness matrix K is assembled and the stiffness parameters

are obtained using the direct stiffness method: For every global unit deformation i (e.g. constant strain, shear, bending) a corresponding displacement field is applied to the outside of the unit cell via nodal displacements (displacement vector u_i) and the resulting nodal forces (force vector F_i) are calculated by $F_i = \mathbf{K}u_i$. By combining these nodal forces into a global force or moment corresponding to each unit deformation, a fully analytic description of the effective stiffness parameters is then obtained.
To illustrate this method, it is carried out for the classic Miura origami pattern (see Figure 1) in two cases; unconstrained and constrained by face sheets on both sides. A parameter study is performed, and the results are compared to literature.

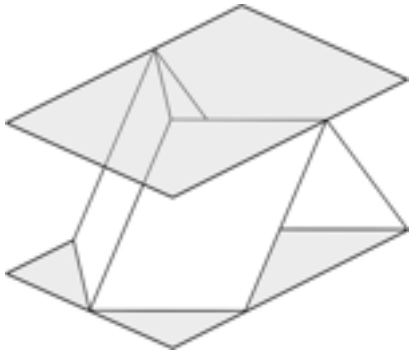


Figure 1. The unit cell of the Miura origami pattern with face sheets on top and bottom

3. Results / Conclusions

A homogenisation of the mechanical properties of folded sandwich structures based on an analytic approach is presented and validated against literature. This enables efficient optimisation of an arbitrary folded sandwich structure and lays the foundation for further investigations, e.g. stability or modal analysis of such structures.

Broadband Flow Control via Lattices of Coiled Phononic Subsurfaces

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[2]University of Colorado Boulder, USA
[3]University of Maryland, USA

1. Introduction / Objectives

The delay of laminar-to-turbulent flow transition is essential for reducing skin-friction drag and enhancing the fuel efficiency of future sustainable aircraft. This study introduces an advanced smart material concept based on lattices of phononic subsurfaces (PSubs), as seen in Figure 1(a), built with coiled internal geometries to achieve passive, broadband flow control. Unlike conventional active techniques, PSub structures are designed to respond out-of-phase to growing Tollmien-Schlichting waves, attenuating flow instabilities at the source without embedding obstacles in the fluid domain in a phenomenon called "scatterless interferences". The goal is to break the narrow bandwidth limitations of conventional resonant structures by leveraging multi-point flow interaction. Combining Bloch-wave theory with machine learning-driven geometric optimization, this research aims to design

lightweight, structurally integrated smart PSub structures capable of broadband and sustained downstream flow stabilization.

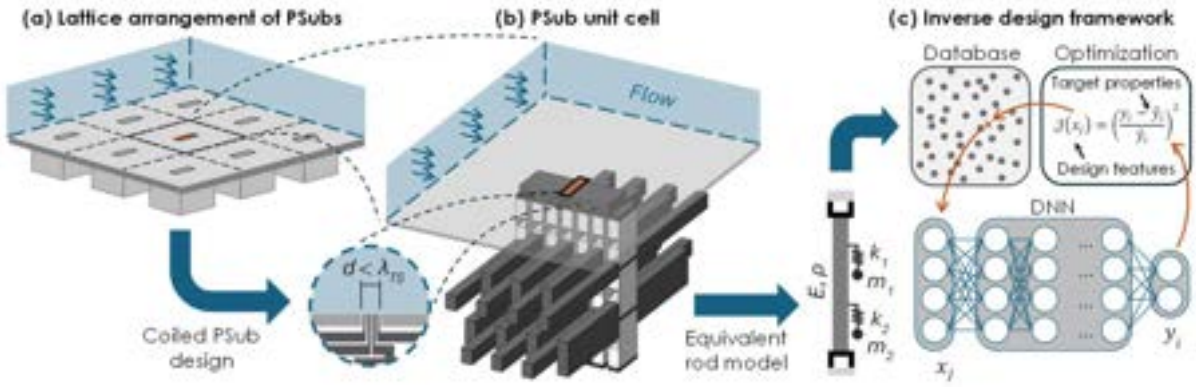


Figure 1. *(a) Schematic representation of the lattice arrangement of the phononic subsurface (PSub) structure. (b) Detail of the coiled PSub unit cell with multiple concentrated points of interaction with the flow. (c) Inverse design framework using a simplified rod model to build a database linking geometrical features to effective properties.*

2. Methodology

The methodology integrates multi-scale modeling, machine learning, and high-fidelity fluid-structure interaction (FSI) simulations. First, a spatial Bloch-wave formulation is applied to a unit cell comprising the flow interacting with the PSub lattice. By incorporating frequency-dependent complex admittance boundary conditions into the generalized Orr-Sommerfeld equations, the dispersion behavior of the unstable flow modes is predicted across full-span, square, and hexagonal lattice symmetries. To broaden the operational bandwidth, a coiled PSub configuration is implemented, creating multiple structural connectivity points with the flow as depicted in Figure 1(b). By applying rotational locking at the turning junctions, the longitudinal and transversal deformations are uncoupled, ensuring the core phonon band gaps are preserved. This enables the complex 3D coiled layout to be accurately mapped onto a simplified 1D linear elastic rod model containing a periodic array of spring-mass resonators.

To bridge the gap between targeted elastodynamic properties and practical manufacturing geometries, an inverse design framework is established (see Figure 1(c)). Geometrical features across distinct structural layers are randomized to generate a database of effective homogenized parameters. Deep neural networks (DNNs) are subsequently trained as surrogate models to interpolate within this space, and a Genetic Algorithm (GA) optimizes the 3D internal configuration to achieve the desired broadband "super resonance" metrics. Finally, the optimized smart composite layout is validated using Direct Numerical Simulations (DNS) of the 3D incompressible Navier–Stokes equations. The FSI coupling is enforced at the interface using linear transpiration boundary conditions that match fluid and structural velocities while maintaining a low roughness Reynolds number. Post-processing incorporates a comprehensive flow integral analysis framework to systematically evaluate the attenuation of perturbation kinetic energy and decompose the individual physical contributions to the skin-friction drag coefficient.

3. Results / Conclusions

The results demonstrate that lattices of phononic subsurfaces establish sustained downstream decay of perturbation kinetic energy, providing explicit verification of delayed laminar-to-turbulent transition. Both the square and hexagonal PSub lattice configurations demonstrate excellent robustness, achieving stabilization that is immune to variations in the propagation angle of incoming instability waves. Furthermore, the coiled subsurface design successfully breaks traditional bandwidth limits, realizing broadband flow control without incurring a structural or aerodynamic penalty. The machine learning inverse design loop accurately maps the optimized target effective properties back into manufacturable multi-layer geometries. In conclusion, enabling subsurface phonon engineering with optimized coiled design of PSubs introduces a paradigm shift in aerodynamic surface design. It shifts the focus from purely external streamlined shaping toward internal, passive, wave-synchronized structural manipulation, offering a transformative, highly sustainable path for skin-friction drag reduction in next-generation aircraft components.

Multidisciplinary Design Optimization of Aircraft Structures

Chaired by:
Dr. Dietrich Knörzer (Former Senior Officer, Aviation Unit, DG Research & Innovation, European Commission)

Aircraft Mission-Based Climate Impact Surrogate Modeling for Engine Pre-Design

Nils Roth, Patrick Egerer, Rafael Balderas-Xicohtencatl
Bauhaus Luftfahrt, Germany

1. Introduction / Objectives

The decarbonization of aviation requires not only alternative propulsion concepts, but also new methods to assess their full climate impact during early design stages. Hydrogen-fueled aero engines offer a significant potential to reduce the overall climate impact of civil aviation but depend strongly on non-CO_2 effects, including nitrogen oxides (NO_x) and contrail formation, whose relevance varies with atmospheric and operational conditions. Existing climate-assessment approaches are often computationally intensive or insufficiently detailed for engine pre-design applications.
Within the publicly funded HyKliK project, Bauhaus Luftfahrt develops climate impact surrogate models and mission-based climate metrics suitable for integration into engine predesign workflows. The proposed approach enables a rapid estimation of mission-level climate effects from a representative engine operating point while accounting for performance characteristics such as altitude, specific fuel consumption, NO_x emissions and engine mass. This provides a novel capability to directly include climate metrics in multidisciplinary engine optimization and conceptual aircraft design.

2. Methodology

Establishing the link between engine pre-design and the resulting climate impact of a flight

mission requires the integration of three different modeling steps: engine design, aircraft design and climate response.

The engine design for the desired performance requirements is done in GasTurb and exported in the form of tabulated data. The subsequent aircraft design and assessment is performed using the Bauhaus Luftfahrt Aircraft Design Environment which interpolates the engine deck to determine the engine performance and emissions for all desired conditions. The full aircraft design loop is run for varying engine characteristics to evaluate snowball effects and design consequences following different engine properties. First, based on a calibrated reference aircraft, a future kerosene-driven aircraft with entry-into-service 2035+ is derived which is then converted into a future hydrogen aircraft. This process has been developed for a regional aircraft based on an ATR72 as well as a short-medium-range (SMR) aircraft based on an A320. The simulated emission data from the design mission is read by the in-house developed simple response climate model based on Wiegand et aL. It computes the corresponding climate metrics for CO_2, NO_x, soot, and water vapor emissions, as well as contrail induced cloudiness.
This toolchain is executed for a full factorial combination of varying engine performance characteristics which results in a large dataset connecting the engine parameters: thrust-specific fuel consumption, thrust-to-weight ratio, cruising altitude and NO_x emission index with its corresponding climate metric. This dataset is then used to train models of varying complexity to allow for an efficient and quick computation of climate metrics already in the engine pre-design loop. The complex interactions can be reduced to equations that can be solved analytically – allowing for the derivation of handbook methods for climate impact calculations. The errors resulting from these simplifications are assessed by comparing the full fidelity calculations with the prediction model results.

3. Results / Conclusions

While for regional aircraft, a dual-aft-tank system provides sufficient storage space, for SMR aircraft a front- and aft-tank configuration is chosen to minimize the center-of-gravity shift during flight. The resulting aircraft show significant performance impacts for small engine performance changes. Only the variation in NO_x emission characteristics does not require a new sizing loop to result in converged aircraft designs.
Evaluating different modeling approaches showed that already a linear regression of second order could show most expected trends and tradeoffs necessary for the engine pre-design when the deviation of the characteristics remain close to the training data. A visualization of the efficacy-weighted Global Warming Potential (EAGWP) in CO_2-equivalent for different input parameters can be seen in Figure for a hydrogen aircraft with the maximum assumptions for contrail effects. To improve the reliability of the results further away from the design conditions, more sophisticated surrogate model approaches are investigated.

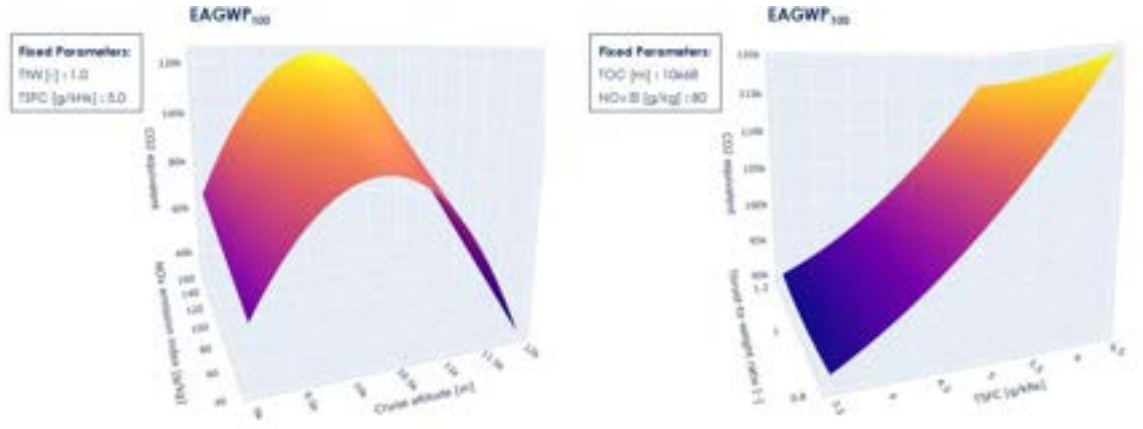


Figure1: EAGWP$_{100}$ results of an LH_2-powered A320 class aircraft for a quadratic regression model with high contrail impact.

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Multi-fidelity aerostructural optimisation of composite wings via RANS adjoint drag sensitivities

Evangelos Filippou, Jurij Sodja, Roeland De Breuker
TU Delft, Netherlands

1. Introduction / Objectives

Although fully coupled high-fidelity aerostructural optimisation is increasingly feasible, its cost remains a major obstacle for design-space exploration with large aerostructural parameterisations, while surrogate-based approaches may introduce approximation errors that mislead gradient-based optimisers. This work introduces a multi-fidelity gradient-coupling strategy in which the static aeroelastic equilibrium is computed with PROTEUS (Werter and De Breuker, 2016), an in-house low-fidelity aeroelastic optimisation framework, and mapped to a RANS model evaluated with DAFoam (He et al., 2020). High-fidelity lift and drag sensitivities are obtained using the discrete adjoint method and propagated to the structural design variables through the PROTEUS aeroelastic Jacobian. As a demonstration case, the framework is applied to a composite-laminate wingbox model of the ONERA M6 wing at subsonic and transonic cruise conditions, demonstrating how the large aerostructural design-space exploration can be handled by a low-fidelity aeroelastic model while RANS adjoints supply targeted high-fidelity aerodynamic sensitivities.

2. Methodology

The static aeroelastic equilibrium and structural sensitivities are computed with PROTEUS, an in-house optimisation framework based on a geometrically nonlinear Timoshenko beam model coupled to a Vortex Lattice Method. The ONERA M6 composite wingbox model has a semi-span of 1.196 m and an aspect ratio of approximately 3.8. Its wingbox is divided into

seven spanwise design sections and four structural components: upper skin, lower skin, front spar, and rear spar, resulting in 28 laminate zones. Each zone is parameterised by eight lamination parameters, four in-plane and four bending-stiffness terms, together with one ply-thickness variable, giving 252 structural design variables. At each outer optimisation iteration, PROTEUS performs a trim-consistent cruise analysis and returns the deformation snapshot, the trimmed angle of attack, and the full twist Jacobian with respect to the structural design variables at 16 spanwise stations. Structural constraints include buckling, principal strain, and laminate-feasibility constraints.

The high-fidelity aerodynamic component uses DAFoam, an open-source discrete-adjoint framework based on OpenFOAM. The PROTEUS deformation snapshot is imposed on the ONERA M6 RANS mesh through a Free-Form Deformation parameterisation at the same 16 spanwise stations. One steady RANS primal solve and two adjoint solves provide the lift and drag sensitivities with respect to the deformation variables. These sensitivities are then combined with the PROTEUS aeroelastic Jacobian through the chain rule,

$$\frac{\partial D}{\partial x} = \left(\frac{\partial D}{\partial \tilde{\theta}}\right)_{\text{DAFoam}} \left(\frac{\partial \tilde{\theta}}{\partial x}\right)_{\text{PROTEUS}},$$

and analogously for lift. A Python orchestrator manages the exchange between PROTEUS, DAFoam, and the GCMMA optimizer (Svanberg, 2002). The objective is a Breguet-form aerostructural range function combining RANS lift and drag with the structural mass and trim state from PROTEUS. Two cruise conditions are considered: subsonic, EAS = 170 m/s and $M_\infty = 0.50$, and transonic, EAS = 285 m/s and $M_\infty = 0.82$.

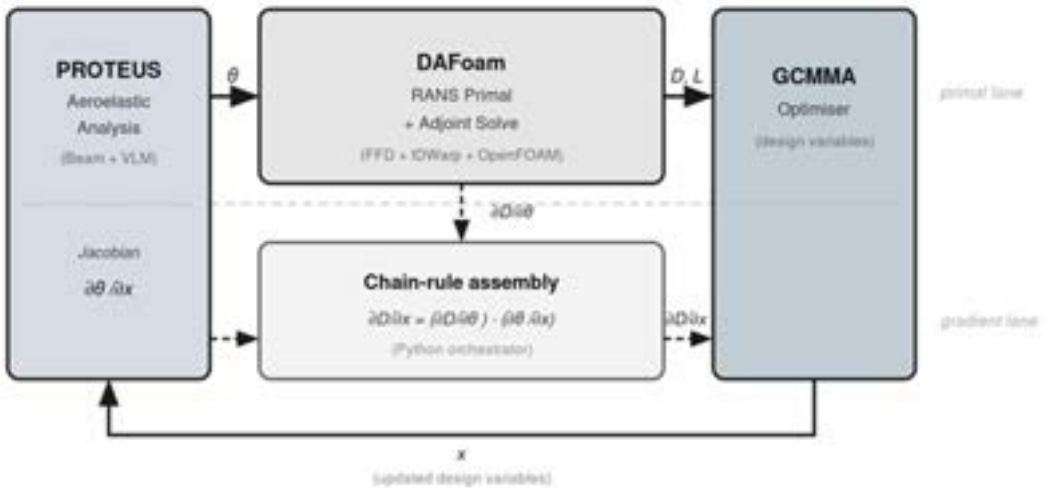


Figure 1. *Multi-fidelity coupling architecture: GCMMA drives PROTEUS (beam+VLM) for the aeroelastic snapshot and twist Jacobian, passed to DAFoam (RANS adjoint). Chain-rule assembly returns drag gradients w.r.t. all design variables from a single primal and two adjoint solves per iteration.*

3. Results / Conclusions

Coupled aerostructural optimisations were completed for both cruise conditions within a 72-hour wall-time budget on the DelftBlue supercomputer. At subsonic cruise, $M_\infty = 0.50$, the optimiser achieved an 8.5% improvement in the aerostructural range objective over 25 outer GCMMA iterations, with a 56.9% reduction in wingbox mass from 4.68 kg to 2.02 kg, while cruise drag remained approximately constant at 300 N. At transonic cruise, $M_\infty = 0.82$, a 7.2% range improvement was obtained with a 42.7% mass reduction from 4.68 kg to 2.68 kg, while drag was approximately four times higher, around 1270 N, due to wave drag. In both cases, the range gain is primarily mass-driven, as expected from the Breguet-type surrogate. The results confirm adjoint-chain-rule coupling as a viable strategy for high-fidelity laminate optimisation with large design-variable counts. Ongoing work extends the framework to include control-surface deflection sensitivities and apply it to high-aspect-ratio transport wings for manoeuvre-load alleviation.

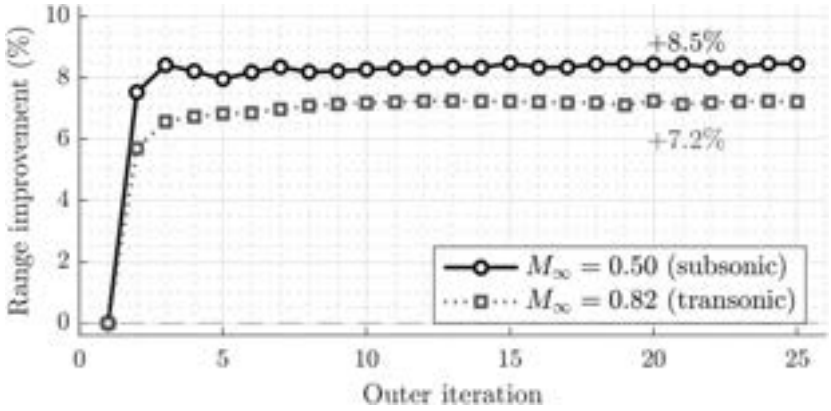


Figure 2. *Convergence of R (improvement relative to the initial design) at subsonic ($M_\infty = 0.50$) and transonic ($M_\infty = 0.82$) cruise. Both cases converge within 25 outer GCMMA iterations to gains of 8.5 % and 7.2 %, respectively.*

A Training-Oriented Hydrogen, Kerosene, and Battery Aircraft Design MDO Problem with Uncertainties

Dajung Kim[1], Thierry Druot[1],Nicolas Peteilh[1], Omar Hammami[2], Matthias De Lozzo[3], François Gallard[3]

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[2]ENSTA, France

[3]IRT Saint Exupery, France

1. Introduction / Objectives

Aircraft conceptual design involves strongly coupled disciplines such as aerodynamics, structures, propulsion, and mission performance, making multidisciplinary design optimization (MDO) essential. Frameworks such as GEMSEO and OpenMDAO have simplified the implementation of MDO workflows; however, suitable training-oriented problems remain limited. The Sobieski supersonic business jet problem is one of the most widely used ones. Nevertheless, its fixed configuration and limited physical interpretability, due to the use of arbitrary interpolation data across disciplines, restrict its relevance in education. In addition,

UQ methods require specific modeling, such as the definition of uncertain variables. This paper proposes an open-source (https://gitlab.com/gemseo/dev/gemseo-oad-training) configurable aircraft design benchmark problem for MDO training that is independent of the MDO framework. The models support conventional, hydrogen, and electric powered aircraft within 14 disciplines, with physically meaningful design variables and uncertainty modeling to enable multidisciplinary trade-offs, suitable for multiple educational levels within Bloom's taxonomy.

2. Methodology

The proposed benchmark couples 14 disciplines into simple Python functions compatible with GEMSEO and OpenMDAO. Users can define deterministic or uncertain design variables, objectives, and constraints according to specific training goals. The relatively large number of disciplines and the particular sparse coupling structure are suited to better understand the concepts of coupling graphs, compared to other benchmark problems where the N2 matrix is very dense. The main disciplines included in the model are:

Geometry. Wingspan and fuselage length are derived from the wing area, aspect ratio, and passenger count. For liquid-hydrogen configurations, rear tank length is added to the fuselage, directly coupling tank sizing to aircraft geometry.

Aerodynamics. Zero-lift drag coefficient, induced drag factor, and the cruise lift-to-drag ratio are computed from wing geometry using statistically derived coefficients and the aerodynamic efficiency factor.

Propulsion. Specific fuel consumption SFC and specific energy consumption SEC reflect real turbofan and electrofan thermodynamic characteristics are computed from the bypass ratio using semi-empirical formulas.

Mission. Total fuel m_f, or energy E, is computed via the Brequet equation with a 5% reserve.

Operating cost and CO_2. Cash operating cost and direct operating cost are estimated via the Thorbeck method with fuel-type-specific energy prices. CO_2 emissions are computed from total fuel burn using fuel-specific emission factors.

Constraints. Three performance disciplines provide inequality constraints: take-off field length, approach speed, and the climb rate at the top of the climb, computed from aerodynamic and propulsion outputs. For the rear-tank hydrogen configuration, an additional operational constraint arises, linking the hydrogen tank sizing discipline directly to aircraft geometry feasibility.

Beyond providing a benchmark optimization problem, the proposed formulation incorporates several characteristics intended to enhance configurability, physical interpretability, and uncertainty-aware design exploration.

Multi-configuration support. Fuel type and engine type switch the entire discipline chain between conventional kerosene, liquid-hydrogen turbofan, liquid-hydrogen electrofan, and battery-electric configurations without modifying any disciplinary model.

Uncertainty modeling. Selected model parameters can be treated as uncertain variables, enabling sensitivity analyses and uncertainty propagation studies.

Interpretability. The use of physically grounded constants ensures that optimized outputs are directly interpretable and verifiable against known aircraft data.

3. Results / Conclusions

The benchmark has been used for multiple years in graduate-level GEMSEO practical sessions at ENAC and ENSTA, two leading French engineering schools, involving

approximately 20 students per institution annually. The disciplinary coupling structure of students' assignments is illustrated in Figure 1. Students performed constrained multidisciplinary optimization studies across kerosene and liquid-hydrogen configurations, compared active constraints, and interpreted mass breakdown. Sensitivity analyses on the hydrogen tank gravimetric index (Figure 2) and passenger-range Pareto front explorations demonstrated the benchmark's capacity to support meaningful multidisciplinary design exploration.



***Figure1**. N2 diagram of the hydrogen-powered aircraft sizing optimization example, illustrating coupling interactions among the disciplinary models.*

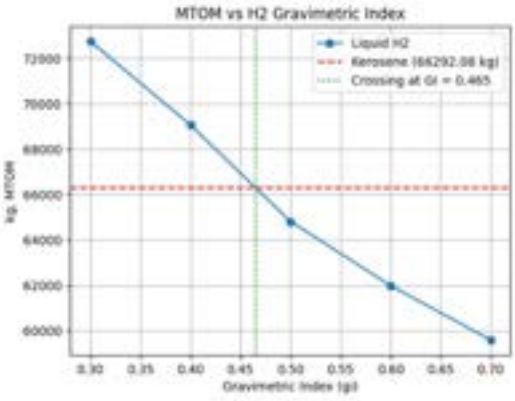


***Figure2**. MTOM as a function of hydrogen tank gravimetric index, compared with the kerosene reference aircraft. The two configurations reach equivalent MTOM at GI=0.465.*

Compared with classical benchmark problems such as the Sobieski test problem, the proposed formulation provides greater configurability and a closer alignment with realistic aircraft design trade-offs. As AI-assisted design increasingly enables the exploration of larger and more complex design spaces, MDO proficiency is becoming an essential skill for future aerospace engineers. The proposed benchmark addresses this need by providing a physically interpretable and configurable training environment.

Multidisciplinary Design of High Aspect Ratio Wings: Maximising Active Load Alleviation via Control Surface Topology Optimisation

Armand-Ioan Curpanaru[1,2], Philippe Pastor[1], Fabrice Demourant[2], Eric Nguyen Van[2]
[1]ISAE-SUPAERO, France
[2]ONERA, France

1. Introduction

Facing 5% annual air traffic growth and fuel costs exceeding 45% of operational expenditures, the aviation sector must meet stringent sustainability mandates. To achieve these targets, minimising drag is critical. While High Aspect Ratio Wings (HARW) maximise aerodynamic efficiency, their slender geometry induces severe aeroelastic coupling. Consequently, the structural weight required to stiffen these flexible wings fundamentally limits their aerodynamic gains. Active load alleviation is indispensable here. Mitigating manoeuvre and atmospheric loads reduces structural forces, enabling weight and performance gains.

While research is transitioning toward integrated aeroservoelastic Co-Design, current methods typically optimise control layouts on fixed baselines rather than concurrently updating the aerostructure. Furthermore, their isolation from global vehicle models leaves broader multidisciplinary impacts unexplored.
Addressing these gaps, this paper introduces an aeroservoelastic framework that evolves the authors' previous research by elevating control surface positioning to a primary design variable. By integrating this dynamic layout with structural sizing and robust controller synthesis, the framework captures complex multidisciplinary interactions. This study demonstrates the critical impact of aileron configuration on GLA performance, proving this fully coupled approach is essential for preliminary aircraft design.

2. Methodology

To achieve these objectives, the methodology employs a fully parametric aeroservoelastic Co-Design framework. Baseline aircraft sizing via FAST-OAD is seamlessly coupled with SHARPy, which handles aeroelastic wing modelling, linear model generation, and dynamic simulations alongside an integrated robust H-infinity controller synthesis module. The framework's primary advancement is a novel adaptive meshing algorithm developed specifically for active control surface layout optimisation. To optimise this configuration, the structural and aerodynamic meshes dynamically adapt to the aileron's parametric spanwise position and dimensions. By recalculating geometric boundaries and linearly spaced coordinates across three wing segments, the algorithm computes exact mass and stiffness matrices for every adapted finite element. This guarantees a highly precise geometric representation of the control surface, independent of the global spatial discretisation.
Figure 1 illustrates the framework's workflow during a Multidisciplinary Design Optimisation (MDO) run, where an optimiser drives the Multidisciplinary Design Analysis (MDA) loop. Initially, baseline data from FAST-OAD and outputs from the adaptive mesh are processed by Data Mapping blocks to generate the exact input files required by the SHARPy aeroelastic solver. Following model generation, a static aeroelastic simulation calculates the cruise trim angle of attack. The workflow then branches: if GLA is inactive, the nonlinear model undergoes an open-loop dynamic gust simulation. Conversely, if active, the model is linearised to synthesise a robust controller before executing a closed-loop dynamic simulation. Finally, critical structural loads from either path are extracted and fed back into the MDA loop for wing resizing, repeating the cycle until convergence yields the optimised design.

3. Results

To leverage this framework, an optimisation problem is formulated to minimise wing structural mass. The control surface's spanwise position is treated as a design variable, constrained within geometric bounds (indicated by the red dotted lines in Figure 2) while maintaining a fixed spanwise width. The optimisation is executed across various Aspect Ratios (AR) for parametric sensitivity analysis. The results (Figure 2) demonstrate the significant impact of structural flexibility: as AR increases, the optimal spanwise position shifts progressively inboard. Finally, the complete article will benchmark this mass-driven MDO architecture against an alternative MDA approach, where control surface positioning and robust controller synthesis are concurrently optimised. This future work will systematically evaluate the resulting aeroservoelastic design trends of both methodologies.

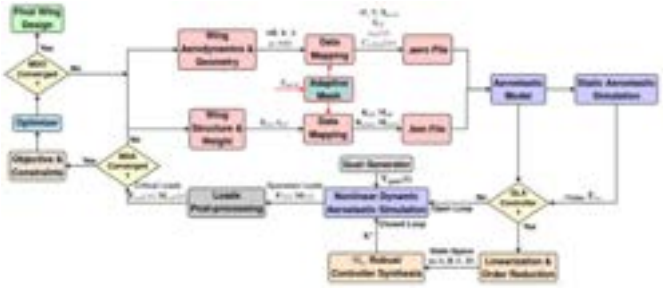


Figure 1. *Workflow of the Aeroservoelastic Design Framework surface layout*

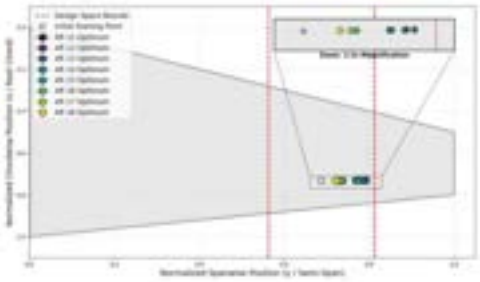


Figure 2. *AR impact on optimal control*

System of Systems Optimization for Robust Autonomous Air Cargo Operations

Ruben E. Perez[1], Jeremy C.-H. Wang[1,2]
[1]Royal Military College of Canada
[2]Ribbit Inc

1. Introduction / Objectives

Air cargo operations serve an essential role providing supplies to rural or isolated communities as well as moving time-sensitive deliveries for both urban and rural customers. Previous work has shown how the use of a System of Systems (SoS) approach that couples the design of aircraft configurations with the operational assignments of such aircraft can provide both higher utilization of existing resources at lower operational costs. This coupled effect is further enhanced with the introduction of resilient pilotless flight technologies. This paper extends the previous body of work by introducing a system of systems methodology that optimizes air cargo operations with additional consideration for uncertain operational demand. This type of demand typically arises when single occurrence time-sensitive cargo needs to be transported, such as is the case with emergency medical supplies deliveries or critical transport of components or manufacturing materials.

2. Methodology

The general methodology used in this research is depicted in Figure 1. The network design problem is modelled as a dynamic resource allocation problem, whereby the cargo to be transported represents the resource being allocated to optimize a given utility function based on cost and time operational efficiencies. To account for uncertainty in operations, a monte-carlo sampling approach is used which solves the assignment problem as defined from regular network operations and a number of non-scheduled demand instances that followed known distributions of non-regularly operated demand origin, destination pairs and their corresponding cargo requirements. The aircraft performance and corresponding cost of operations when allocated to the air freight network are determined using an object-oriented, multi-fidelity aircraft conceptual design framework.
Application of the methodology is made in the context of an air cargo logistic network in Canada, which combines regular service to both populated and remote northern areas and encounters a considerable number of single-demand cargo events. The regular demand information for the network is provided from a model based on geographic and socio-economic parameters that affect the demand for air cargo. The unscheduled demand is

provided from historical information and statistical distribution of single occurrence cargo flights.

3. Results / Conclusions

Results show the optimal autonomous aircraft design configurations for the fully scheduled network and the mixed scheduled/unscheduled cargo demand network. Comparison and trade-offs between both solutions in their ability to meet the network's demands are also shown. It is shown how the systems of systems approach shifting the configuration designs to higher payload-range-efficient levels, which leads to more profitable operations for lower-demand routes and unscheduled cargo delivery events. Thereby, extending the possibility to provide wider coverage into remote and isolated communities or better handle time-critical operations.

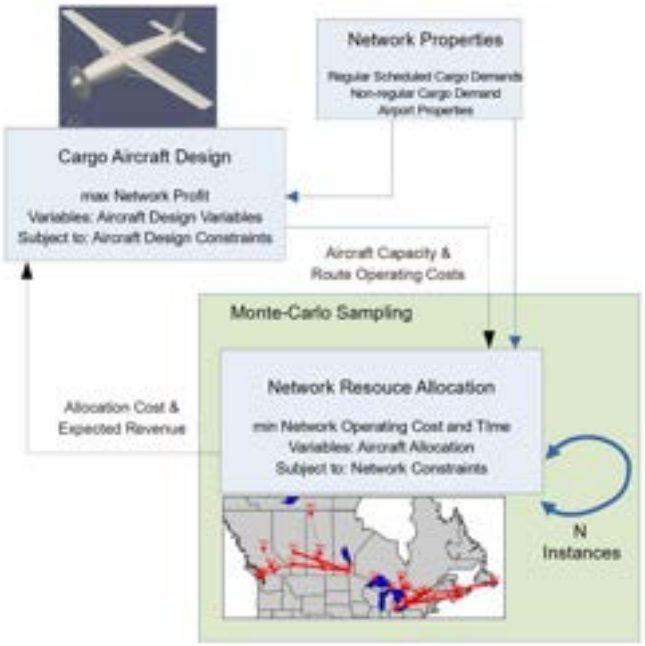


Figure 1. *SoS Optimization of Coupled Aircraft and Air-Cargo Network with Uncertainty*

Understanding hydrogen-air combustion in aeroengines (HESTIA Final Event)

Chaired by:
Mr. Marc Truscelli (SAFRAN Group, France)

HESTIA: Hydrogen combustion in aeroengines

Nicholas Treleaven, Marc Truscelli
SAFRAN Group, France

1. Introduction / Objectives

To reduce the climate impact of aviation, decarbonisation is a major challenge. Current aircraft engines burn hydrocarbon fuels such as kerosene or, more recently, emerging SAF products (Sustainable Aviation Fuels). Hydrogen is also considered as a promising fuel, but the burning of hydrogen creates radically new challenges that need to be understood and anticipated. The HESTIA project focused on increasing the scientific knowledge of hydrogen-air combustion for future hydrogen-fueled aero-engines. Different challenges are addressed in HESTIA: improvement of the understanding of turbulent hydrogen-air combustion, including preferential diffusion of hydrogen, modification of the turbulent burning velocity, thermoacoustics, NOx (Nitrous Oxides) emissions, and adaptation of optical diagnostics); assessment of innovative injection systems for H_2-optimized combustion chambers (flashback risk, lean-blow out, stability, NOx emission minimisation, ignition); and improvement of CFD tools and methodologies for numerical modelling of H_2 combustion in both academic and industrial configurations.

2. Methodology

The HESTIA project was completed in two phases: a first phase of basic research and a second phase of applied research; and three technical work packages. Both of these phases included experimental and numerical approaches including the interaction of complex and varied physical phenomena. The academic and basic research phase has investigated the three major research fields: understanding of H_2/air combustion key phenomena such as stabilization, flashback, ignition, pollutant emissions and heat transfer through fundamental experiments; flame dynamics of H2/air combustion to understand the response of H_2 flames to acoustics; and modelling of elementary processes involved in turbulent reactive flows of H_2/air mixtures. The applied research phase built upon the basic research phase to develop and consolidate experimental and numerical methods dedicated to design, and evaluated several H_2 injector concepts, first in lab-conditions, and then in aero engine representative conditions (equivalence ratio, pressure, temperature).

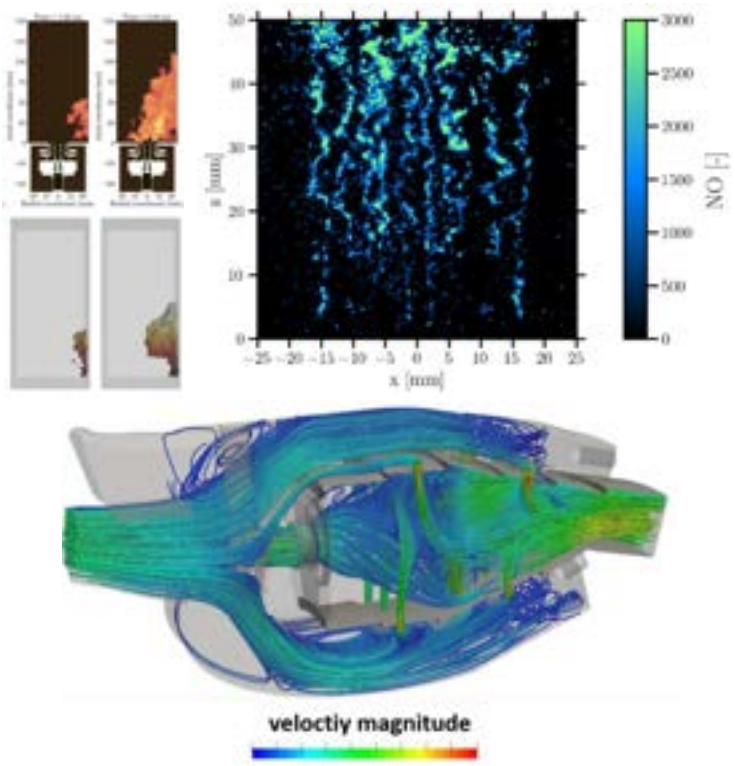


Figure 1. *Examples from each work package Left: Simulations of ignition of a swirl stabilized injector (WP1). Centre: Experimental measurements of NO produced by strut injectors (WP2). Right: MTU aeroengine baseline case (WP3).*

3. Results / Conclusions

An example of the some of the results produced is shown in Figure 1. Since the start of HESTIA in 2022, fundamental studies have brought a better understanding of H_2/air combustion. In particular, new modelling techniques have unlocked advanced multi-physics simulations adapted for the specificity of hydrogen, which, in turn, enables us to better capture relevant phenomena (e.g. flame stabilization, pollutants, etc.). Numerous lab-scale test rigs have been commissioned and are being used to test a wide variety of promising injectors. These experimental results will also constitute a pillar against which models and simulations can be validated. New diagnostics, new tools and, in general, best engineering practices have been transposed to hydrogen injectors — whether incremental improvements or breakthrough technologies. Furthermore, new archetypes of flames have been thoroughly investigated.

Mastering key phenomena of H2/air combustion

Benoît Fiorina, Etienne Espada
CNRS, France

1. Introduction / Objectives

One of the work streams of the HESTIA project is to study and describe fundamental physical processes involved in turbulent H_2/air aeronautical combustors by conducting in parallel theoretical studies, high-fidelity experiments, and high-performance computations. The objectives are: to understand the mechanisms involved in flame stabilisation; identify the routes responsible for nitrogen oxide formation; predict and control the thermo-acoustic instabilities; analyse the influence of film cooling on the flame properties; develop an experimental database; and develop turbulent combustion models for CFD adapted to aeronautical combustors.

2. Methodology

In order to achieve these objectives HESTIA developed four complementary test benches for the investigation of turbulent hydrogen–air combustion. Advanced diagnostic and experimental techniques have been designed and validated; they include among others, laser-based NOx field measurement, acoustic excitation at different locations or a specific modular dual-channel test rig for stratification analysis. Thermoacoustic low-order modelling and validation using experimental data generated within the project was also performed. Numerical modelling activities are being carried out concurrently, in most cases using the experimental data for comparison and validation purposes. In the area of flame dynamics and thermoacoustic instabilities, Lattice-Boltzmann methods are being explored as a simulation approach, and Flame Transfer Functions (FTF) are derived from CFD. As regards chemistry, two simplified strategies were investigated: one based on flamelet-tabulated models, and the other on optimized mechanisms. A dedicated DNS framework has also been established for model validation. This extensive work is completed by the modelling of H2 ignition process.

3. Results / Conclusions

An extensive set of experimental results were obtained using specific test rigs, integrating modular systems where key parameters like pre-mixing, swirl, cross-flow position, acoustic forcing can be modified and analyzed. Various types of injection systems were tested, including some quite different from typical aerospace configurations. The physical characteristics were measured using a combination of advanced measurement techniques providing flame images, velocity, OH, OH*, mixture fractions fields, pressure at the walls and gas chemical composition. This allowed a fine description of flame structures, flame dynamics and the associated key parameters.
It is observed that stable hydrogen flames of various shapes can be obtained. The study of self-sustained combustion oscillations shows the dependence on synchronization with hydrodynamic and acoustic phenomena.
On the numerical side, multiple developments have led to simulations representing very well the main trends described experimentally, with most of the work focusing on low-pressure cases. Various types of simulations were carried out, namely CFD RANS, LES, DNS and LBM, all showing satisfactory results and comparisons. For thermo-acoustics, Flame Transfer Functions

have been derived from CFD, and in another approach Hybrid LBM explored. As regards chemical modelling, new flamelet-based and virtual chemistry models were successfully developed and implemented, in the latter case also modelling NOx formation mechanisms.

Injection systems design – incremental & breakthrough technologies

Thomas Komarek
MTU Aero Engines, Germany

1.Introduction / Objectives

The HESTIA project seeks to mature several H_2 incremental and breakthrough injection concepts for aero engines through a combination of analytical and experimental results. The goal is to ultimately deliver cross-comparison of the different H_2 injection concepts to select the best configurations; a selection of recommended optimized H_2 injection concepts that can provide a significant reduction of NOx emission (-50 to -80% relative to kerosene-powered technologies); a risk evaluation for the selected concepts; and a roadmap to mature H2 injection technology to TRL6.
In this presentation, we will show how different concepts can be developed by analysing the effects of key design parameters by means of advanced experimental and numerical tools, and how this will contribute to design recommendations and guidance for H2 combustion systems.

2.Methodology

In HESTIA, the exploration of these H2 injection systems has complementary approaches and contributions:

- Setup and operation of highly modular injection systems where the effect of key design parameters can be studied and lead to recommendations.
- Development of incremental systems for retrofit into existing (kerosene) engine, in a realistic mid-term approach of H2 implementation in aeroengines.
- Development of disruptive injection technologies specifically tuned for hydrogen combustion.

In order to deliver these objectives, HESTIA carried out:

- Experimental investigation of H_2 combustion with different mix levels with CH4 and different premixed levels.
- Numerical simulations to capture the effects of mixedness with H_2 combustion.
- Design of an optimized H_2 mixer with regards to NOx emissions and safety margins with regards to flashback and autoignition.
- Experimental investigation of strut injectors for micromixing while preserving thermal resistance of the walls.
- Investigation of novel fuel injection technologies based on distributed/multi-point injection.
- Development of RQL and lean burn H_2 injector concepts.

Experimental investigations used advanced techniques such as stereo PIV, OH-PLIF, NO-PLIF laser-based diagnostics so as to enable detailed understanding of the flame structures and combustion mechanisms at play.

3. Results / Conclusions

Explorations with an academic swirl burner have led to several conclusions. Increased premixing lengths led to reduced stability margins and elevated flashback risk. The jet momentum relative to the H2 crossflow (JIC), emerged as a key parameter influencing flame stabilization. Higher JIC ratios promoted rapid mixing and facilitated bluff-body-like flame stabilization. Emissions were also studied, and a a non-negligible contribution of NO_2 was observed at lean conditions, emphasizing the need to account for both NO and NO_2 in low-NOx evaluations.

Various other injector designs have been explored, including among others, lean burn, non-premixed, multipoint H_2 injector concepts that have potential for better control of NOx compared to conventional RQL based designs while minimising risk of flashback associated with premixed concepts. CFD assessment of direct injection concepts were developed from fundamental scaling studies.

The concept of strut injectors was improved by controlling the flame length and consequently reducing the level of NOx emissions. This was first tested at atmospheric pressure and subsequently confirmed at higher pressure levels, showing that disruptive technologies can emerge as very valid options for H2 combustion in aeroengines.

H2 combustion technology specifications and operability assessments in representative aircraft conditions

Murthy Ravikanti
Rolls Royce, UK

1. Introduction / Objectives

HESTIA seeks to carry out numerical assessment and optimisation of H_2 injector concepts within practical combustor configurations and aeroengine representative conditions. This is where all the outcomes and scientific outputs from the project feed into potential industry applications.

Are also included in the work plan, low-TRL testing (up to TRL3) of H_2 injector concepts at atmospheric, elevated pressure and low pressure (altitude-relight like) conditions to characterise NOx vs. stability/operability trade. The aim is to evaluate of the relative performance benefits and risks for aircraft application and to define TRL6 roadmap for the maturation of most promising technologies.

2. Methodology

The strategy here is to transfer fundamental studies carried out in the project, into practical concepts of aeroengine configurations, and perform a combination of numerical and experimental studies to assess these concepts in realistic operational conditions.

This includes:

- CFD validation of RQL and micro-mix style injectors integrated in a realistic combustion chamber which is sized with respect to H2 flame volume.
- Adaptation of a commercial combustion system model with a H2 injection system with the goal of studying combustion and component thermals through conjugate heat transfer CFD. For the study, a reverse-engineered geometry of a well-known IAE V2500 combustion chamber is used.
- Development of H2 multipoint injection concepts at atmospheric pressure, with emissions measurements to characterize NOx vs operability and obtain the optimal design range. This is followed by more representative high-pressure testing on a test rig specifically designed and built for this purpose.
- Testing on a test rig specifically created for this task, of low-NOx combustor technology with respect to: safe operation in the entire operating range including ignition and shutdown; NOx Emissions; Flashback and premature autoignition; Injector and combustor thermal loading and overheat.

The analysis of all these contributions will allow to highlight the main difficulties relating to the operation of H2 combustion systems in conditions representatives of aeroengines, and consequently define key targets and a roadmap for development of their maturity to TRL6 level.

3. Results / Conclusions

Results obtained so far have shown that:
Several H2 injection technologies show functional performance in line with requirements for aerospace applications, including breakthrough concepts that the industry is not familiar with. NOx emissions in particular can be controlled to very low levels.
Simulation tools can be adapted to hydrogen and compare very well to experimental data, although much less validation data is available at pressures higher than atmospheric, which require attention.
As expected, the existing design rules for kerosene injectors have to be reconsidered. Mixing, flame size and temperature are quite different with hydrogen. In addition, known risks of flashback have to be carefully looked at.
While it is more convenient to size the combustion chamber around the H2 flame proportions, it is possible to design H2 injectors that can be retrofitted to existing combustors.

Next Generation Efficient Airframe Production: Materials, Automation and Lightweight Design

Chaired by:
Dr. Andreas Battenberg (Fraunhofer, Germany)

Beyond the Test Pyramid: A New Approach for Certification of Emerging Materials and Structures

John-Alan Pascoe
TU Delft, Germany

1. Introduction / Objectives

Current aerostructures are certified with the aid of the so-called 'building block' or 'test pyramid' approach (Figure). This approach is based on first characterizing material properties through coupon testing. Geometrical effects and structural aspects are then progressively introduced by testing specimens of increasing complexity.

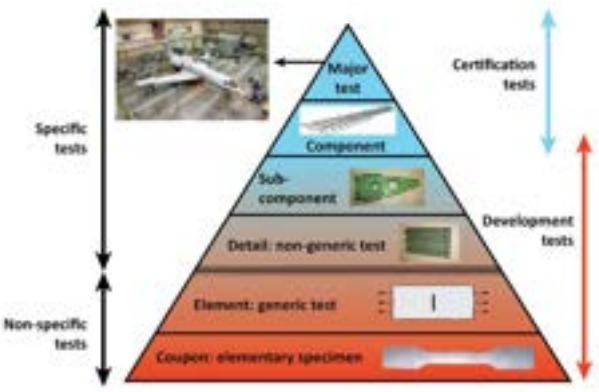


Figure 1 Test pyramid approach to certification of aerostructures reproduced, licensed under CC-BY-NC-SA 4.0.

A key implicit assumption of the building block approach is that there is a clear distinction between a 'material' and a 'structure'. However, this distinction is increasingly disappearing: for both composite materials and additive manufacturing processes, we create the structure and the material at the same time. While the test pyramid approach is still used, it leads to constricting design freedom (e.g. limiting designers to qualified lay-ups) and requires extensive testing of complex structures for certification of additive manufacturing.

2. Methodology

To take full advantage of the design freedom of composite materials and additive manufacturing, a new certification approach is needed, which can drastically reduce the time and cost needed to support certification. Figure schematically illustrates the new certification approach proposed in this work, which consists of three key pillars: (1) understanding of the physics, (2) process monitoring, and (3) performance based acceptance.

Understanding of the physics: For many current cases, design substantiation is based on empirical (i.e. data driven) correlations. For example, the Paris relationship for fatigue crack growth is based on a fit through experimental data, not a derivation from underlying physical laws. Consequently, extensive test campaigns are necessary to support certification, because test results cannot be generalized. This issue is amplified for composite materials; this

contribution will highlight recent work showing that coupon tests are not sufficient for characterizing the failure modes seen at structural scales. Thus, there is a challenge for academia to investigate more deeply the underlying physics, to create more efficient testing approaches that can be generalized.

Process monitoring: Currently process monitoring focuses on recording process parameters. Experience and statistical evidence are used to show that if these parameters stay within a specified range, the resulting part quality will be acceptable. Instead, with ongoing advances in sensors and process modelling, we should be able to build up a map of part quality and especially assess the effects of process anomalies on the resulting part features (e.g. microstructure or local fibre orientation).

Simulation based acceptance: At present a frozen process specification is used for manufacturing and parts are accepted for service based on statistical sampling. However, if the condition of each individual part is known in sufficient detail, and the physics of failure are well enough understood, a performance prediction could be generated for each individual part. Then part acceptance could be done on the basis of that predicted performance. This would allow for greater processing flexibility and a first time right approach, because minor process variations or anomalies could be accounted for directly, without necessitating a full requalification.

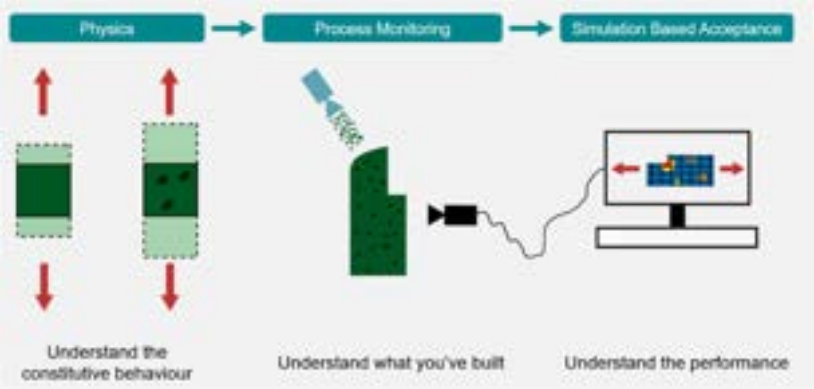


Figure1: Proposed new certification approach

3. Conclusions

The proposed certification approach has the potential to drastically reduce the test effort required to support aerostructure certification, especially in the case of emerging concepts such as variable stiffness laminates or additive manufacturing. However, achieving this approach in practice requires scientific advancements in the areas of process monitoring and modelling, as well as a better understanding of the physics of failure. The present contribution therefore seeks to inspire collaboration, and to define a research agenda to accelerate the certification of novel aerospace structures and materials.

Structural Mass Optimization of Boeing 787 Components Using CFRP-Kevlar Hybrid Composites for Fuel and Emissions Reduction

Mykyta Koliesnik
Odesa Lyceum, Ukraine

1. Introduction / Objectives

The aviation industry is constantly on the lookout for structural innovations that can reduce aircraft weight without compromising safety, performance, and economic efficiency. The use of carbon-fiber-reinforced polymer (CFRP) as a standard material for modern aircraft structures has been a practice for many years. In this paper, the feasibility of implementing a CFRP-Kevlar hybrid composite in selected structural parts of the Boeing 787 is studied. The objective is to evaluate the impact of partial material substitution on the weight, fuel consumption, carbon dioxide emissions, and operational economics of aircraft. The goal of the work is to identify structural groups in which hybrid composites can be used without completely redesigning the aircraft while maintaining the load-bearing capacity of primary structures.

2. Methodology

As a representative member of the Dreamliner family, Boeing 787-9 was chosen as a baseline model for the analysis. Structural components were grouped into seven categories: wing control surfaces, wing skins, ribs, stringers, interior panels, luggage compartments, fuselage secondary structures, and service covers. Material replacement was not considered for primary load-bearing elements such as spars and fuel tank structures in order to maintain conservative safety assumptions. The internal structure of a representative aircraft wing considered in the analysis is illustrated in ***Fig.1.*** The CFRP-Kevlar laminate stacking sequence adopted for the material evaluation is shown in ***Fig.2.*** Density scaling relationships between conventional CFRP, aluminum, GFRP, and a CFRP-Kevlar hybrid composite were used to estimate mass reduction [2,3]. The component masses for the Boeing 787 variants were derived using published aircraft mass breakdown data and proportional scaling factors. Classical flight mechanics-based analytical aircraft performance models were used to evaluate the effect of structural mass reduction on the aircraft performance [4,5]. Fuel consumption was calculated from range-dependent calculations using a given aircraft weight, lift-to-drag ratio, wing area, cruise conditions, and thrust-specific fuel consumption. Annual operational benefits were based on weighted route distributions and estimated annual utilization profiles. Carbon dioxide reduction was calculated using standard aviation fuel emission factors, and economic benefits were estimated according to average prices of Jet A-1 fuel.

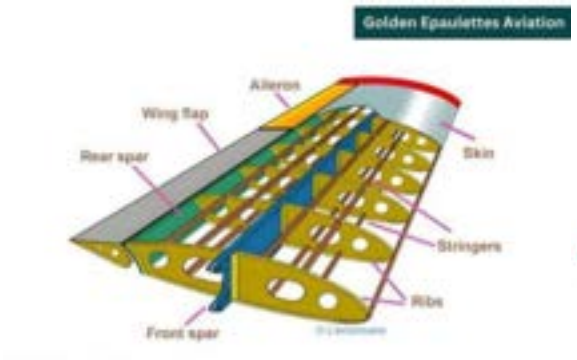


Figure 1. Internal structure of a wing composite

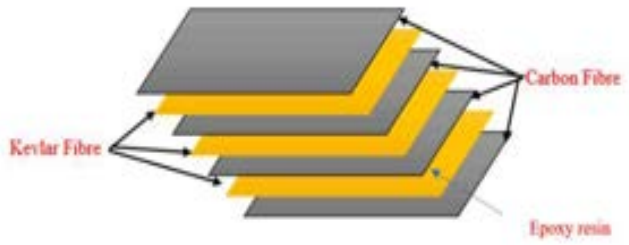


Figure 2. Sequence of laying carbon-Kevlar

3. Results / Conclusions

The research suggests that a partial replacement of selected Boeing 787 structural parts with CFRP-Kevlar hybrid composites can achieve a weight reduction of approximately 9.0 tons for the Boeing 787-9 configuration, which is about 3.5% of the maximum takeoff weight. This results in reduced fuel consumption, which provides substantial operational benefits over one year of aircraft service. Fuel savings are estimated to be in excess of several hundred tonnes per year per aircraft, equivalent to around 2500 tonnes of avoided CO2 emissions and economic savings of nearly USD 0.6 million per aircraft per year. The results indicate that the incorporation of hybrid composites into non-critical and secondary aircraft structures may be a feasible approach to enhance aircraft sustainability and operational efficiency with only modest increases in certification complexity and redesign effort.

Surrogate-Assisted Layout and Sizing Optimization of a Composite Wingbox Using Automated GFEM Generation

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1. Introduction

Early-stage aircraft structural design requires the evaluation of multiple layouts in limited time while still capturing the behaviour of composite structures. Conventional preliminary sizing often relies on empirical wing-mass models and historical data, which can be insufficient for novel configurations or composite wingboxes. Physics-based Finite Element (FE) models can improve fidelity, but they are usually time-consuming to create manually, while repeated structural analyses or sizing optimisations can introduce a large computational cost. This work aims at developing an automated, physics-based workflow for rapid structural layout exploration of composite airframes. The main contribution is the coupling of parametric GFEM generation, composite sizing optimisation, and Gaussian-process-based Bayesian optimisation (BO), so that different wingbox layouts can be assessed using a limited number of expensive finite-element sizing runs. The approach is demonstrated and validated on the

Simple Transonic Wing (STW) benchmark and is intended as a step towards more reliable preliminary design tools for composite aircraft structures.

2. Methodology

The suggested workflow is implemented through in-house Python modules that automatically generate HyperMesh TCL scripts. For each candidate layout, an analysis-ready GFEM of the STW wingbox is created, modelling upper and lower skins, front and rear spar webs and caps, ribs, and T-shaped stringers. Composite components are modelled using CFRP ply-based properties, while ribs are simulated as Aluminium shell components. Two manoeuvre load cases are considered , corresponding to +2.5g pull-up and -1g pull-down conditions, with strength and linear buckling analyses used inside the sizing process.

The optimisation is formulated as a nested layout-sizing problem, following the general idea of multilevel aircraft structural optimisation and related nested wingbox layout-sizing studies. The outer loop involves three layout variables: the number of ribs, the number of stringers per skin panel, and the width of the spar caps. For each fixed layout, a gradient-based inner loop performs component sizing. The sizing vector contains 75 variables, including ply-thickness variables for the orientations (0◦,±45◦ and 90◦) in three span-wise sizing zones, together with metallic rib-thickness variables. The sizing problem minimises the wingbox structural mass subject to composite and aluminium rib strength constraints, a first-buckling-eigenvalue requirement, and manufacturing constraints on ply percentages. A staged multi-run strategy is used to reduce local-minimum sensitivity: feasible sizing results are warm-started and followed by a progressively tightened mass upper bound.

A Gaussian-process surrogate is trained to approximate the optimised mass as a function of the layout variables. Gaus- sian processes are well suited for low-data surrogate modelling as they provide both non-linear regression and predictive uncertainty, which can be used inside surrogate-based optimisation. The initial design set contains 24 optimised Latin- hypercube layouts. BO then selects six additional layouts using an improvement-based infill criterion, following the efficient global optimisation principle. This gives a total budget of 30 expensive nested evaluations. A nested MIDACO global-search run is used as a reference for comparison and validation.

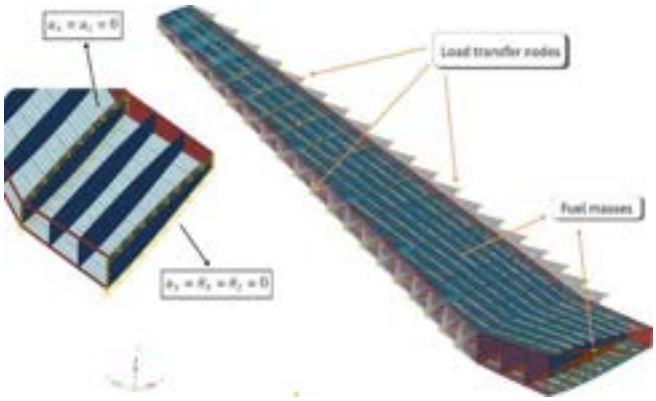


Figure 1: STW wingbox GFEM used for the nested layout-sizing optimization

3. Results / Conclusions

The BO study identified the best layout (Nribs, Nstr, wcap) = (23, 13, 50 mm), with an optimised structural mass of 1737.35 kg. This improved the best initial DoE design by 45.26 kg, corresponding to a 2.54% mass reduction. The nested MIDACO reference found a very similar layout, (23, 13, 48.61 mm), with a mass of 1732.24 kg after 152 expensive layout evaluations. The 5.11 kg difference between the two solutions is small relative to the observed variability of the inner-loop sizing process, while both methods recover the same optimum layout region. However, BO required only 30 evaluations, an 80.3% computational reduction compared to MIDACO. The results show the effectiveness of automated GFEM generation combined with surrogate- assisted optimisation in supporting early-stage composite wingbox design with substantially reduced computational cost.

Table 1: Best observed layouts and computational effort.

Method	N_{ribs}	N_{str}	w_{cap} [mm]	Mass [kg] / evals
Best initial DoE	23	9	45.62	1782.61 / 24
BO, 24+6	23	13	50.00	1737.35 / 30
Nested MIDACO	23	13	48.61	1732.24 / 152

The Application of Physics-Informed Neural Networks for Structural Strength Enhancement

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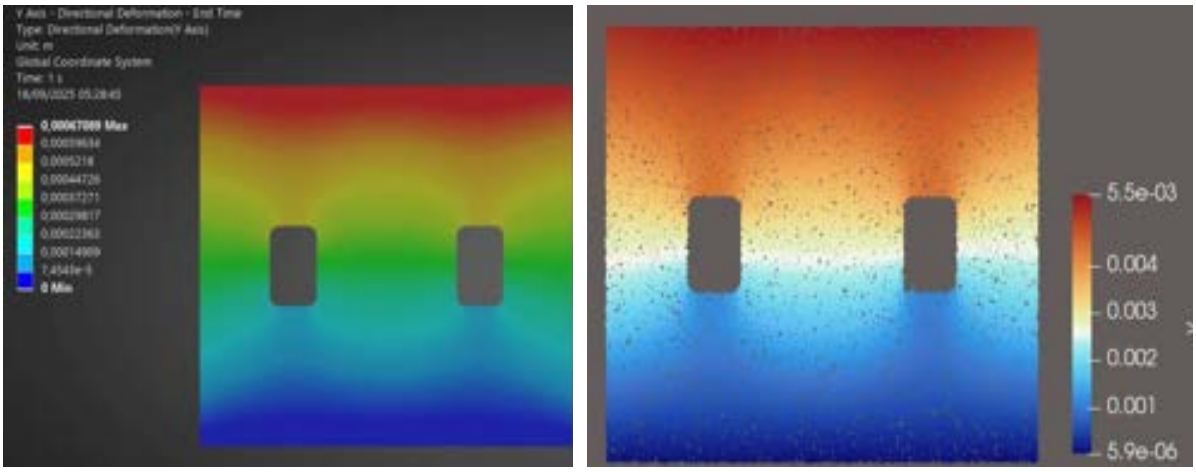
1. Introduction

Traditional structural design and optimization of aerospace components heavily rely on finite element analysis, which is computationally intensive and limits iterative design exploration. This study introduces a new potential approach to airframe design and optimization that leverages Physics-Informed Neural Networks (PINNs) to accelerate structural analysis and enhance load-bearing capacity. The main objective is to evaluate alternative structural solutions for a typical airframe by integrating governing mechanical equations directly into the deep learning training process. The main difference in this work lies in replacing traditional, decoupled parametric FEA sweeps with a continuous, physics-constrained exploration of the design space. By embedding elastic field equations into the loss function, the framework enables real-time structural evaluations of complex geometries. This methodology establishes a new and efficient paradigm for next-generation aerospace structural design, overcoming the computational bottlenecks of conventional state-of-the-art numerical solvers.

2. Methodology

The proposed methodology complements conventional numerical discretization by incorporating deep learning models that are constrained by fundamental physical laws. The structural domain of a typical airframe section is modeled using the NVIDIA Modulus (formerly Physics-Informed Neural Operator/Modulus, referencing the specialized Physics-ML

framework) platform, which provides advanced accelerated solvers for PINN implementation.
Network architecture is trained using a multi-objective loss function that incorporates boundary conditions and the governing partial differential equations (PDEs) of linear elasticity and structural mechanics, with mass constraints. This setup ensures that the network predictions inherently satisfy mass, momentum, and stress equilibrium conditions without requiring a traditional mesh.
The design exploration focuses on three critical airframe components to maximize structural efficiency and strength-to-weight ratios: (i) variable section stiffeners, considering geometric parameters of the stiffener profiles are treated as continuous inputs, allowing the network to evaluate complex, non-uniform cross-sections; (ii) variable section frames, with frame geometries that are optimized to distribute heavy localized loads more uniformly and (iii) variable thickness skin panels, where the skin panel thickness is modeled as a spatial variable to reinforce regions subjected to high stress gradients while minimizing weight in low-stress zones.
NVIDIA PhysicsNeMo simulates the displacement, strain, and stress fields across these interconnected structural elements. Automated optimization loops process the continuous inference data generated by the PINN, mapping structural assessment across a vast geometric design space to identify optimal combinations of configurations that maximize overall structural strength.



a) FEA simulation *b) PINNs inference*

Figure 1. *FEA vs. PINNs inference for a fuselage panel (vertical displacement).*

3. Results / Conclusions

The implementation of PINNs via NVIDIA PhysicsNeMo generated alternative airframe configurations featuring optimized variable-section profiles and tailored skin thicknesses. The physics-informed framework agreed with baseline structural benchmarks and reduced computational evaluation times by several orders of magnitude compared to traditional FEA. The resulting airframe solutions exhibited significant enhancements in localized structural strength and optimized stress distribution without incurring a weight penalty. These findings

underscore the potential impact of Physics-ML in aerospace engineering, proving that PINNs can serve as a viable, high-fidelity tool for real-time structural synthesis. This approach paves the way for faster design and optimization cycles and allows for exploring new alternatives for more sustainable aircraft architecture.

Multiscale Modelling and Machine Learning of Shock-Absorbing Hyper-Elastic Metamaterials for Aerospace Payload Protection

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1. Introduction / Objectives

The development of next-generation aerospace structures demands advanced impact and vibration mitigation systems to ensure the structural integrity of critical components. In this context, this work focuses on developing computational tools for the design of shock-absorbing dissipative metamaterials characterized by rapid shape recovery and high-frequency impact resilience. While hyper-elastic constituent materials at the microscale are typically non-dissipative, this study demonstrates that macroscopic dissipation can be achieved through the emergence of a non-convex free energy. The main objectives of this research are: 1) to formulate a numerical tool capable of accurately predicting the energy dissipated during an impact; 2) to characterize the evolution and velocity of the shock wave propagating within the macroscopic body as a result of transitions between the stable phases of the material; and 3) to evaluate the potential of these metamaterials as protective shielding elements for vibration-sensitive aerospace payloads

2. Methodology

To model these materials, a framework based on multiscale theory is proposed. The macroscopic solid domain (2D/3D) is coupled with a microscale microstructure defined by a periodic lattice architecture composed of slender, buckling-capable elements. This multiscale framework efficiently handles the unmatched dimensions between scales while precluding numerical instabilities through the use of dimension-perturbed buckling layers within the Representative Volume Element (RVE). The integration of Machine Learning (ML) techniques is proposed to automate and accelerate the material characterization pipeline. Specifically, classical neural networks and Gaussian process regression methods are studied to construct a microscale surrogate model. This model is trained using homogenized data from multiple microscale experiments, enabling near-instantaneous prediction of effective material properties.

3. Results / Conclusions

The results demonstrate the excellent energy-dissipating capacity of the proposed metamaterial and its sensitivity to geometrical variations in both the macroscale domain and the microscale RVE architecture. Furthermore, detailed insights regarding the morphology and propagation speed of the internal shock wave generated by the material phase

changes are provided. It is concluded that incorporating Machine Learning-based surrogate models constitutes a highly efficient alternative to accelerate the analysis of complex metamaterials without compromising physical accuracy. Finally, the dynamic analysis validates the great potential of these systems as realistic, ultra-lightweight solutions for vibration isolation and energy absorption in aerospace structures, opening a promising avenue for protecting satellite instrumentation and sensitive payloads during critical mission phases such as launch or re-entry.

Navigation and Control Onboard Systems

Chaired by:
Prof. Cezary Szczepanski (Warsaw Institute of Aviation, Poland)

Motor control Electronics for Flight Control Actuators, A Trade Study of Architecture and System-Level Packaging

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1. Introduction / Objectives

High aspect ratio (HAR) wing architectures are a cornerstone of next-generation aircraft design, aiming to drastically reduce aerodynamic drag and thereby improve fuel efficiency. Within the Clean Aviation project Ultra Performance Wing (UPWING), advanced high-performance wing concepts are being investigated for future ultra-efficient short- and medium-range (SMR) aircraft.
The proposed wing architecture enables significant reductions in fuel consumption and CO_2 emissions. However, HAR wings also impose strict spatial constraints due to their thin structure, particularly for flight control mechanisms and actuators. Consequently, the development of compact flight control actuators represents a key challenge.
This paper presents technologies for compact motor control electronics (MCE) as part of an electromechanical actuation system. Two different architectures and system-level packaging approaches are investigated, and their performance is compared.

2. Methodology

This paper investigates two motor control electronics architectures based on the available aircraft power supply, namely HVDC 540 V and 115 V AC at 360–720 Hz (Fig. 1). In addition, two different system-level packaging approaches for the MCE output stage are analyzed to evaluate their compliance with aircraft requirements regarding thermal performance, weight, volume, electromagnetic interference (EMI), and related constraints.

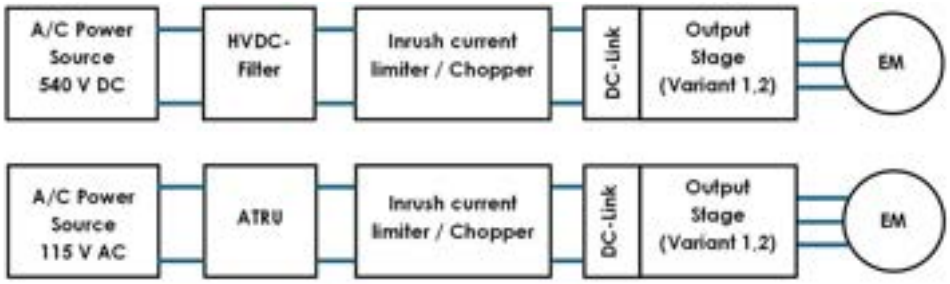


Figure 1. *Comparison of two MCE with different input stage architectures and packaging variants of the output stage*

The study is based on the development of circuit topologies and the sizing of key electrical components. Following the definition of circuit topologies and component selection, power losses are calculated for both architectures and packaging approaches.
With regard to the packaging variants, the focus is mainly on the thermal behavior of the power semiconductors and the associated thermal management strategies. Since both packaging variants exhibit approximately identical weight and volume, these parameters are not significantly influenced by the packaging choice. Based on these findings, thermal analyses are performed to evaluate system behavior under various operating conditions. Furthermore, the MTBF was estimated for both AC and HVDC input stage as well as complete MCE.
Considering a representative flight mission profile, thermal management simulations are conducted to estimate the required heat sink geometry and housing design needed to comply with aircraft requirements. Finally, the weight and volume of each architecture and packaging solution are evaluated and compared.
In this trade-off study, the common modules such as the output filter and control electronics - including sensor processing and communication - are not considered, as these elements are identical across both architectures and output stage packaging variants.

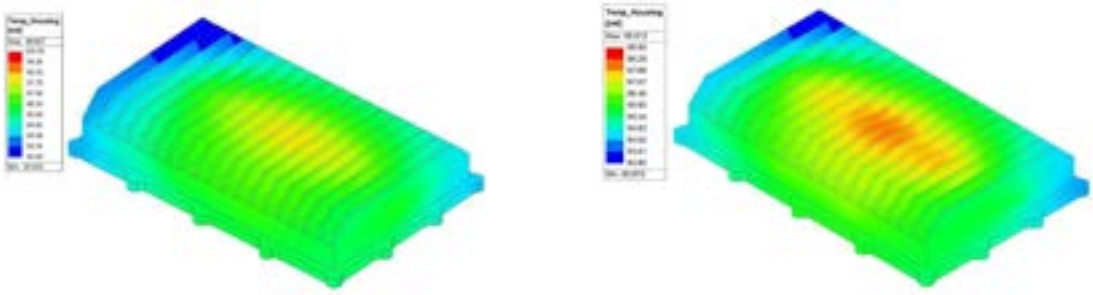


Figure 2. *Comparison of thermal behavior of the output stage with two packaging variants under identical loading and environmental conditions*

3. Results / Conclusions

According to the designed circuits and the sizing of the key components, the following results are obtained:

- The power loss of the AC-input stage is significantly higher than the HVDC-input stage with factor 27 at maximum load for the same packaging variant. This difference is primarily attributed to the losses in autotransformer rectifier unit (ATRU), which is required to convert AC power to DC.
- Consequently, the AC architecture exhibits higher weight and volume compared to the HVDC architecture, with factors of 3 and 1.5, respectively, for identical packaging variants. This is mainly due to the heavy ATRU and the need for a larger heat sink to dissipate the additional losses.

Both packaging variants 1and 2 show comparable performance in terms of thermal behavior as well as weight and volume.

Comparison of Classical and Neural Network-Based Approaches for UAV Trajectory Prediction

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[2]Warsaw University of Technology, Poland

1. Introduction

Trajectory prediction of UAVs is an important topic, particularly in recent years. Drones can be used for malicious purposes such as espionage, armed attacks, disruption of critical infrastructure, smuggling, and others. To enhance the safety of areas exposed to such threats, counter-UAS systems are widely employed. To effectively neutralize a target, these systems must predict its future position at the next time step in order to apply appropriate countermeasures, such as kinetic effectors or jamming. This research addresses the problem of UAV trajectory prediction. The main objective is to identify the most suitable method for implementation in a kinetic counter-drone system. The study compares classical methods, which often rely on simplifying assumptions, with neural network–based approaches. The scientific innovation lies in the evaluation of these fundamentally different methods under the same operational conditions and in assessing their respective advantages and limitations.

2. Methodology

The main objective in this research is the comparison of two approaches to UAV trajectory prediction problem. One of the approaches is based on classical methods which rely on mathematical models of system dynamics. The research takes into account the simple velocity integration, linear regression methods and Kalman Filtering. The other method is based on neural network approach, the LSTM (Long Short-Term Memory) network was selected. All of the methods will be tested in the same conditions, to fulfill this requirement the trajectories of the targets must be identical across all tested methods. To thoroughly compare and evaluate these methods a large set of flight trajectories was tested. This allows for a clear evaluation of the advantages and limitations of each methods. Different types of trajectories and maneuvers will be evaluated to assess the performance of the prediction. To generate a set of different trajectories the function to create randomly waypoints of the planned flight path was developed. These points are generated in a specific area provided by the user, the requirements about the minimum distance and angle between neighboring points are also taken into account. The sample of the planned trajectory is shown in Figure 1.

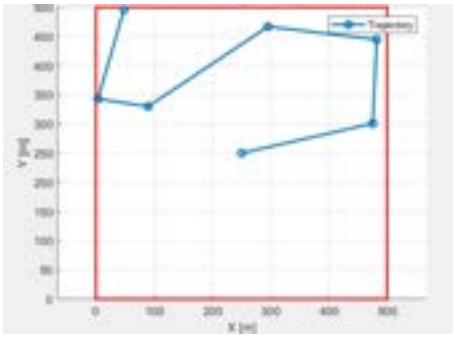


Figure 1. *Random UAV trajectory.*

Then, the trajectory is implemented in the UAV system simulator and the modelled UAV is trying to follow the generated trajectory. At this stage of the research the quadcopter was selected for this purpose. The result of the simulation is the drone real flight trajectory. The results are used to compare and evaluate the performance of the considered prediction methods. The prediction horizon is set to 2 seconds, the errors from each of the methods are compared during different maneuvers and flight phases. The example of the result method showing the performance of the algorithms is presented in Figure 2 where the error between the flight and predicted trajectory is presented.

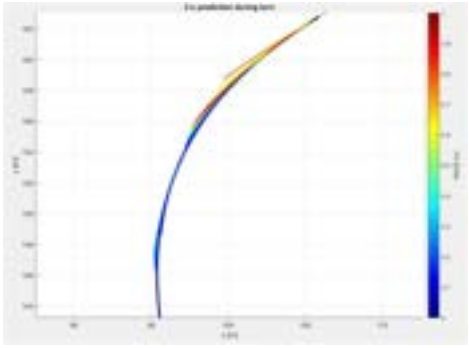


Figure 2. *Example of research results.*

3. Results

Presented results allows to compare the performance of the selected trajectory prediction algorithms during different phases of the UAV mission. This research confirmed that all of the methods are able to predict the flight trajectory of the UAV. Their performance differs depending on the flight phase. Classical methods proved effective during stable flight, while neural network–based methods provide better results during more complex and dynamic flight phases. The results indicate that combining model- and data-driven approaches can further improve prediction performance.

Software-in-the-Loop Validation of Active Disturbance Rejection Control for Autonomous Taxiing of Unmanned Aircraft

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1. Introduction / Objectives

Automation of UAV ground operations, particularly taxiing, remains less developed than airborne autonomy due to strong nonlinearities and disturbances such as tire–ground interaction and crosswinds. Classical controllers often lack robustness under such conditions. This work investigates the use of Active Disturbance Rejection Control (ADRC) for autonomous taxiing of unmanned aircraft, in line with emerging requirements defined in EUROCAE standards ED-251 and ED-284 for RPAS automatic taxiing. The objective is to develop a robust control structure and validate its performance in a Software-in-the-Loop (SIL) environment to ensure realistic and standards-oriented assessment.

2. Methodology

A nonlinear six-degree-of-freedom (6-DOF) model of the MP-02 Czajka UAV was developed to capture essential ground dynamics, including aerodynamic forces, propulsion, and tire–runway interaction modeled using a semi-empirical approach. Landing gear dynamics were represented with a spring–damper system to reflect structural flexibility.
An ADRC-based control system was designed with separate heading and longitudinal velocity loops. Each loop employs a third-order Extended State Observer (ESO) to estimate total disturbances in real time. The control law is based on Nonlinear State Error Feedback (NLSEF), enabling smooth and robust tracking despite nonlinearities and uncertainties.
Validation was performed in a Software-in-the-Loop environment (MATLAB/Simulink). Test scenarios included small (1°) and large (90°) heading step inputs. Performance assessment was aligned with functional expectations defined in ED-284, focusing on tracking accuracy, stability, and control smoothness under representative operational conditions.

3. Results / Conclusions

The ADRC controller achieved stable and accurate heading control across all test scenarios in the Software-in-the-Loop environment. For small inputs, the response showed no overshoot and fast convergence. For large heading changes, the system remained stable, with limited overshoot and settling time.
The SIL validation confirms effective disturbance rejection and compliance with key performance expectations for autonomous taxiing defined in ED-251 and ED-284. The results demonstrate that ADRC is a promising solution for robust UAV taxiing and suitable for further real-time and experimental implementation.

Methods of improving inertial navigation based on terrain-referenced measurements

Krystian Borodacz
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1. Introduction / Objectives

Inertial Navigation Systems (INS) remain one of the fundamental navigation solutions due to their autonomy and independence from external infrastructure. Their primary limitation is the accumulation of errors over time, which necessitates periodic correction using additional information sources. While satellite and radio-navigation systems are commonly employed for this purpose, their availability cannot always be guaranteed.
An alternative approach is to exploit information derived from the surrounding environment. In particular, the Earth's surface can provide a stable reference for navigation updates obtained from various sensors. The objective of this work is to review selected methods of improving inertial navigation using terrain-referenced measurements and to discuss their applicability to different classes of vehicles. Special attention is given to airborne applications and the challenges associated with implementing such techniques on unmanned aerial platforms operating in GNSS-denied environments.

2. Methodology

The presented work combines a review of terrain-referenced navigation methods used to improve inertial navigation with observations gathered during experimental flight campaigns conducted using an unmanned aerial platform.
Selected approaches to reducing inertial navigation drift are analysed with respect to their operating principles, applicability to different classes of vehicles, and suitability for operation in environments where conventional navigation aids are unavailable. Particular attention is devoted to methods utilizing measurements related to the Earth's surface, including techniques based on terrain geometry, visual information, and other terrain-derived features. Their advantages, limitations, and practical implementation challenges are discussed in the context of autonomous navigation.
To support the analysis, a dedicated multi-sensor measurement system was integrated onboard a UAV and several flight-test campaigns were carried out to collect navigation data under realistic operational conditions. The experimental platform enabled the collection of synchronized navigation and terrain-observation data. The acquired datasets were used to assess the practical suitability of different terrain-referenced measurements for navigation support purposes.
The presented methodology allows theoretical considerations to be confronted with experience obtained during real flight operations and provides a basis for evaluating the potential of various terrain-referenced techniques for future multi-sensor navigation systems. Particular attention is devoted to the practical aspects of implementing such methods in real systems, including environmental dependencies, operational constraints or sensor characteristics.

3. Results / Conclusions

The conducted studies indicate that terrain-referenced measurements constitute a promising source of information for reducing inertial navigation drift in situations where conventional

navigation aids are unavailable. However, no single method can be considered universally applicable, as performance strongly depends on environmental conditions and mission characteristics.
Experience gained through flight experiments confirms the feasibility of terrain-referenced navigation for UAV applications and highlights the complementary nature of different sensing technologies. The presented results support the need for development of integrated multi-sensor navigation systems capable of improving robustness and maintaining navigation performance during extended operations in GNSS-denied environments.

Modelling Data Busses

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1. Introduction

During the development of an unmanned aircraft system, which is done with a model based system engineering process, the need of a central information storage about the data busses arose. Since the requirements and the system breakdown were already modelled with SysML, the same model was chosen to store the data bus communication information. Standard SysML did not offer detailed enough stereotypes for the needs, therefore, a profile was created. Additionally, the profile is extended with checks to ensure correct modelling and model exports. The profile and the extending aspects are shown in the paper. The shown profile is used in the aerospace domain, but there are no obvious limitations to this domain.

2. Methodology

The basic top-down approach of systems engineering is valid for the modelling of data buses, too. The modelling starts with definition of the bus in the Internal Block Diagram at a time, when only the need of the connection for data between the system elements is known but not, which data has to be transmitted. The bus then spreads down in a tree topography, ignoring the physical bus topography, into the system elements until device ports are reached. This modelling works very well for busses that do not need additional devices to connect the bus nodes, like CAN and RS485. Busses like Ethernet with their physical (multi-)star topology or point to point connections like RS232 have little disadvantages, when modeled with this concept.
During the next phase of system design the data, mostly variables in the software of the devices, which need to be communicated, is collected. These “variables” are called parameters in the profile. Parameters are documented with their attributes within a table and are related to devices, which create or consume the parameters, by custom relationships. A model check can be used for validation of possible communication paths for the parameters from creator to consumer.
The parameters are composed in the next step to messages. Errors in the composition of the messages like overlapping parameters can be found with a model check. The messages are related to the sending and receiving ports of the devices. Another model check can be used to validate that all parameters that need to be communicated via a bus are contained in at least one message on this bus. Since the messages are signals, they can be used easily in sequence diagrams to describe complicated communication sequences,

which might be needed.
Before being able to implement the communication, the used protocol must be defined. The protocol contains information for the implementor on the bit order as well as header and footer composition.
The modelled information is implemented then, which can be done manually from reading the model directly, but automatic code generation can improve this. Therefore, the profile enables exports for code generation.

3. Conclusions

The shown profile enables modelling of data busses and the communication between devices over them. The profile offers stereotypes for busses, parameters and messages as well as needed stereotypes for relating these elements. Furthermore, a short overview about checking the correctness of the modelling is given. It is shown, how important model exports are for further use of the modelled information. Examples for this are human readable documentation or code generation.

Aircraft Operability: from design to operational performance

Chaired by:
Prof. Joël Jézégou (ISAE-SUPAERO, France)

Selection of Right Maintenance Strategy in Early Aircraft Design based upon a Model-based Methodology

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1. Introduction / Objectives

Aircraft maintenance strategy decisions exert a significant influence on airworthiness, operational availability, and lifecycle cost, yet they are routinely deferred until late in the aircraft development process when key architectural choices have been fixed. This paper addresses that gap by presenting FAMOS (Failure-driven Aircraft Maintenance and Operability Synthesis), a model-based framework for systematic maintenance strategy allocation during early aircraft design. FAMOS maps failure modes to appropriate maintenance strategies such as Condition-Based Maintenance (CBM), Scheduled, Deferred, or Immediate, using normalized failure case. The framework is validated through MaVAM (Maintenance Validation and Assessment Model), a discrete-event simulation environment, which quantifies the operational impact of strategy assignments via metrics including Operational Availability and Maintenance Unavailability. This work demonstrates that embedding structured maintenance reasoning into early design enables more operability-aligned and resilient aircraft programs.

2. Methodology

The proposed methodology is organized into three operational use cases. In the first use case, **Normalize Failure Mode Input**, heterogeneous failure case information is transformed into a structured, decision-ready parameter set comprising attributes such as failure severity, detectability, diagnosability, predictability, and dispatchability, which can be readily employed as filtering conditions within any downstream decision framework. In the second use case, **Allocate Maintenance Strategy**, these normalized parameters are processed through a deterministic evaluation sequence to assign each failure case to the most appropriate maintenance strategy. Strategies considered include Condition-Based Maintenance (CBM), Scheduled Maintenance, Deferred Maintenance (including opportunistic grouping), and Immediate Maintenance as the terminal fallback, with airworthiness and dispatchability constraints enforced as inviolable conditions throughout. In the third use case, **Validate Strategies Through Simulation**, the resulting assignments are transferred to MaVAM (Maintenance Validation and Assessment Model), a state-based discrete-event simulation framework developed in this work and grounded in IATA Aircraft Operational Availability (AOA) principles. MaVAM models the operational and maintenance evolution of a single aircraft over a fixed simulation horizon, computing OTG-based Operational Availability, planned and unplanned grounding contributions, and maintenance absorption across turnaround and overnight stop windows. To validate the methodology, a case study was conducted on 40 representative ATA 32 landing gear failure cases from an A320-class aircraft, comparing FAMOS-derived strategy allocations against a baseline industry portfolio under identical operational assumptions. A complementary CBM sweep analysis was further conducted, progressively varying the proportion of condition-based maintenance from 0 to 100% to quantify the sensitivity of aircraft operability to increasing monitoring maturity.

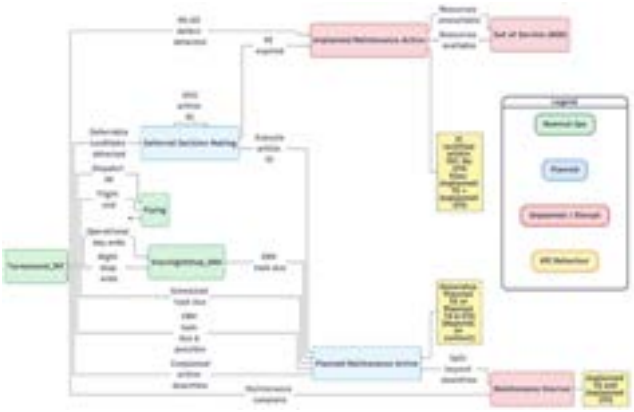


Figure 1. *State-based structure of the MaVAM simulation.*

3. Results / Conclusions

The FAMOS allocation redistributed 55% of the 40 landing gear failure cases toward CBM-oriented strategies, eliminating all immediate maintenance assignments present in the baseline portfolio. Simulation within MaVAM demonstrated an improvement in Operational Availability from 354.34 to 357.04 operational days per year, representing a gain of 2.70 days annually. Total Operational Technical Grounding decreased from 10.66 to 7.85 days per year, with unplanned grounding reduced from 0.87 to 0.20 days per year, indicative of a

substantive reduction in disruptive maintenance events. Total Technical Grounding was further reduced by 3.60 days per year. The CBM sweep analysis established that progressive adoption of condition-aware maintenance strategies could yield up to 6.03 additional operational days per year relative to the fully scheduled baseline, reaching 360.37 days per year at full CBM coverage. Collectively, these findings substantiate that structured, failure-mode-level maintenance strategy allocation during early aircraft design produces quantifiable operability improvements through disciplined, attribute-driven redistribution of maintenance tasks, without necessitating departure from established maintenance philosophy.

Model-Based Operational Effects Analysis

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ISAE-SUPAERO, France

1. Introduction / Objectives

Aircraft are key to an airline's profitability. As high-value assets, operators aim to keep them flying as much as possible since the more a plane flies, the more revenue it generates. Aircraft operations can be disrupted by both scheduled and unscheduled events, the latter including technical failures. An Operational Interruption (OI) is specifically defined as a chargeable interruption of a flight resulting from a technical malfunction of the aircraft or its systems and components. Each detected failure triggers a maintenance action involving material and labor costs, contributing to aircraft downtime. This paper introduces two methodologies for assessing how component failures affect aircraft operations using Model-Based Safety Assessment (MBSA) resources, a growing resource in component certification. One methodology focuses on individual flights, computing the likelihood that specific failure combinations disrupt a given mission. The other takes a broader view, simulating a full year of operations to track operability key performance indicators (KPIs), including operational availability and reliability.

2. Methodology

The proposed methodology combines aircraft operational modelling with Model-Based Safety Assessment (MBSA) resources to evaluate the operational impact of component failures. To project operability results, aircraft operations must be parameterized and described. In this work, operability parameters are divided into three groups: component-level parameters, operational environment parameters and maintenance strategy parameters. Component-level parameters describe the characteristics of individual aircraft components, while operational environment parameters represent the conditions and resources under which maintenance and aircraft operations take place, and maintenance strategy parameters describe the operational policies governing when and where maintenance actions are performed. Component-level parameters include failure rate, repair time, MMEL status, and Risk Priority Number (RPN). Operational environment parameters include maintenance station level parameters such as maintenance technician experience, Human Resources availability, and spare parts availability, and mission level parameters such as turnaround time and mission type.
The second, referred to as the year-long approach, evaluates operability KPIs through a one year of operations simulation. Aircraft behaviour evolves over time due to component

failures and subsequent repairs. The system state is continuously updated and assessed using MBSA minimal cut sets associated with MMEL constraints. This enables the identification of critical situations based on the current and near-future failure state of the aircraft. When such situations occur, operational decisions are taken in accordance with the operational context, and the resulting impacts, including event type and downtime, are recorded. Aggregation over multiple simulation runs provides statistically representative results for operability KPIs.
The methodology is applied to a case study focused on the Airbus A320 nose landing gear system and associated MMEL dependencies.

3. Results / Conclusions

The results allow comparisons and sensitivity studies to assess the influence of the studied parameters on aircraft operability. The main use case of these results is operational decision support, as they can serve as inputs for several types of analyses: early design decisions can be supported by quantifying the impact of component failures, allowing operability-oriented choices when selecting or designing components; spare-part inventory management can also be supported, where critical and frequently failing components can be identified to justify higher spare-part availability, even at increased cost; MMEL-related assessments are enabled by simulating components in the operational environment to evaluate their inclusion in the MMEL or to support trade-offs on rectification interval extensions.

Computational Fluid Dynamics Investigation of Multi-Element Tubercle Wing Design

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Royal Military College of Canada

1. Introduction / Objectives

Aerial vehicles are limited in the lift they can generate due to flow separation at high Angles of Attack (AoA) . This results in reduced manoeuvrability, longer takeoff and landing distances, and lower payload capacity. These limitations can, for example, affect remote communities' access to resources . Traditional high-lift devices, such as slats and flaps, are used to delay stall and increase the maximum lift generated . This paper explores the use of tubercles, a biomimetic implementation of the protuberances on a humpback whale's fin on the leading and trailing edges of a multi-element wing with overlapping tubercle segments. Tubercles have been successfully tested on propellers, rotor blades, and wind turbines, suggesting further applications . The objective is a high-lift system that increases both the stall angle and the lift coefficient while maintaining a drag coefficient comparable to that of a canonical baseline.

2. Methodology

The baseline geometry is the canonical National Aerospace Laboratory (NLR) 7301 main- and flap-airfoil configuration with a 2.6% reference chord gap and a 5.33% reference chord overlap . The NLR 7301 airfoil is commonly used for Computational Fluid Dynamics validation of aircraft high-lift systems . The main element chord is 134.9 mm, and the flap chord is 58.9 mm, with a total reference chord of 184.0 mm, spanning 510 mm. The chord lengths and

span were chosen based on the maximum model size allowable in the Royal Military College of Canada Wind Tunnel.
To determine the effect of tubercles, various configurations of tubercles are applied to the leading and trailing edges of each element of the baseline geometry. The tubercle shapes are defined by a sinusoidal function with amplitude, wavelength, and phase angle as varying parameters. The studied tubercle configurations span a wide range of amplitudes and wavelengths. Phase angles are specified to provide constructive and destructive interference between the main wing trailing edge and the flap leading-edge turbulence shapes.
Each configuration is analyzed under International Standard Atmosphere sea-level conditions. The design point of a Cessna 208 Caravan (C208), given its challenges with short-takeoff-and-landing at higher payloads . As such, the analyses are conducted at the C208's stall speed of 32 m/s, sweeping AoA, focusing on pre- and post-stall behaviour.
Unsteady incompressible flow simulations are performed in OpenFOAM. Turbulence was modelled using a one-equation Spalart-Allmaras Delayed Detached Eddy Simulation. A steady Reynolds Averaged Navier-Stokes simulation was used to initialize the flow field. The C-domain, discretized with a hexahedral mesh, consisted of a curved, uniform-velocity inlet to maintain the same mesh for AoA sweeps, a zero-gradient far-field pressure outlet, and other far-field boundaries as symmetry planes. The wing root was at a symmetry plane, with the tip away from the other symmetry planes, to observe the effects of tip vortices. The steady initialization was discretized using a bounded second-order upwind convective flux solver, and a blended central-upwind scheme was used for the transient solution.

3. Results / Conclusions

The results presented in this paper summarize the aerodynamic performance of various tubercle shapes and configurations, relative to the baseline wing, including lift, drag, and pitching moment. For instance, Figure 1 shows the mean wall shear stress of an overlapping-tubercle configuration, with the main wing trailing-edge and flap leading-edge peaks aligned in phase. The change in mean wall shear stress compared to the rest of the wing behind the tubercles indicates the generation of streamwise, counter-rotating vortices that three-dimensionally compartmentalize the flow. At higher AoA, these vortices can maintain attached flow for longer before separation than a straight leading- and trailing-edge configuration, thereby delaying stall and increasing the maximum lift generated. Ultimately, this improvement in lift generation and stall-angle delay can reduce the required takeoff and landing distances.

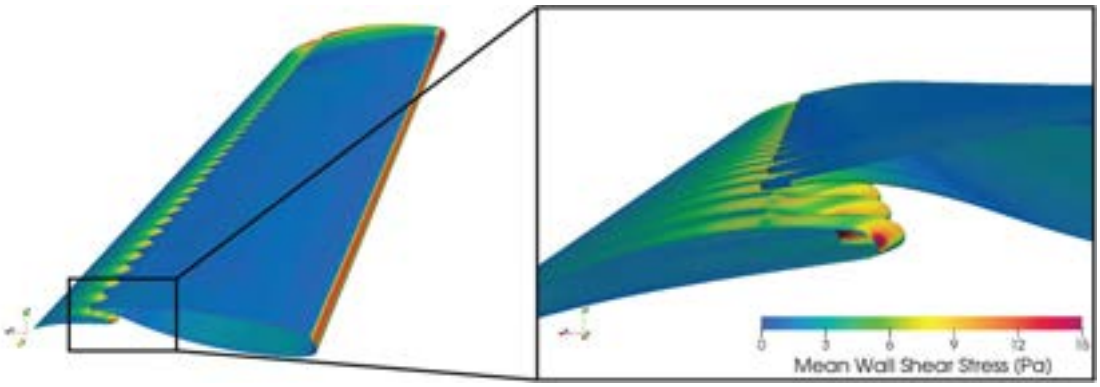


Figure 1. *Mean wall shear stress on overlapping tubercle configuration in phase at AoA of 12°.*

Investigation and Formalisation of the Relationship between Sustainability and Operability

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1. Introduction / Objectives

The aviation industry plays a critical role in global connectivity and economic development; however, it also contributes significantly to environmental impact, with civil aviation accounting for a notable share of global CO_2 emissions and additional non-CO_2 effects further amplifying its climate impact . Aircraft design and operational decision-making have traditionally been driven by operability considerations such as reliability, maintainability, availability, and direct maintenance cost, which remain essential for airline profitability and dispatch reliability . In parallel, sustainability has emerged as a major design driver, focusing on the reduction of life-cycle emissions. Although both domains aim to improve overall system performance, their relationship is not necessarily complementary, as certain design choices simultaneously benefit operability and sustainability, whereas others introduce conflicting trade-offs. Existing approaches generally assess operability and sustainability independently, limiting the ability to analyse subsystem-level interactions during early aircraft design. This work proposes a structured framework to investigate and formalise the relationship between operability and sustainability at aircraft subsystem level and to derive traceable, decision-oriented trade-off metrics applicable during early design stages.

2. Methodology

The Unified Model for Operability and Sustainability (UMOS) is structured into three interconnected levels comprising performance quantification, dependency formalisation, and integrated trade-off evaluation (Figure 1).

The Performance Analysis Model (Level 1) evaluates operability and sustainability independently using surrogate formulations compatible with conceptual aircraft design

maturity. Operability is represented through the Design-stage Operability Risk Index (DORI), formulated as a weighted aggregation of normalised subsystem-level parameters related to maintenance unavailability, maintainability, prognostics capability, scheduled downtime, dispatch flexibility, and operational constraints. Parameter harmonisation is performed using Multi-Attribute Utility Theory (MAUT)-based normalisation with directional consistency, while parameter weighting is derived using the Analytic Hierarchy Process (AHP). Sustainability assessment follows a streamlined lifecycle-based formulation compliant with ISO 14040/14044 principles. Global Warming Potential (GWP) contributions from production, operation, maintenance, and end-of-life phases are aggregated into a subsystem-level CO_2 Intensity Index. Production emissions are estimated using STREAM parametric lifecycle coefficients , while operational emissions are derived from FAA incremental fuel-burn sensitivity factors. The Trade-Off Mapping Model (Level 2) formalises sustainability-operability interactions using a Structural Dependency Network (SDN). The SDN represents subsystem-level dependencies between design attributes, maintenance drivers, operational parameters, and environmental indicators using typed nodes and semantic influence relationships classified as increases, reduces, constraints, or propagates. The network provides structural traceability of complementary and conflicting interactions without numerical propagation.
The Integrated Metrics Model (Level 3) derives decision-oriented trade-off metrics from baseline-relative operability and sustainability deviations. Relative changes ΔO and ΔS are evaluated with respect to a reference configuration and integrated under configurable scenarios corresponding to operability-priority or sustainability-priority modes. The Sustainability Price of Operability (SPO) and Operability Price of Sustainability (OPS) are introduced to quantify cross-domain compensation under explicit trade-off conditions.

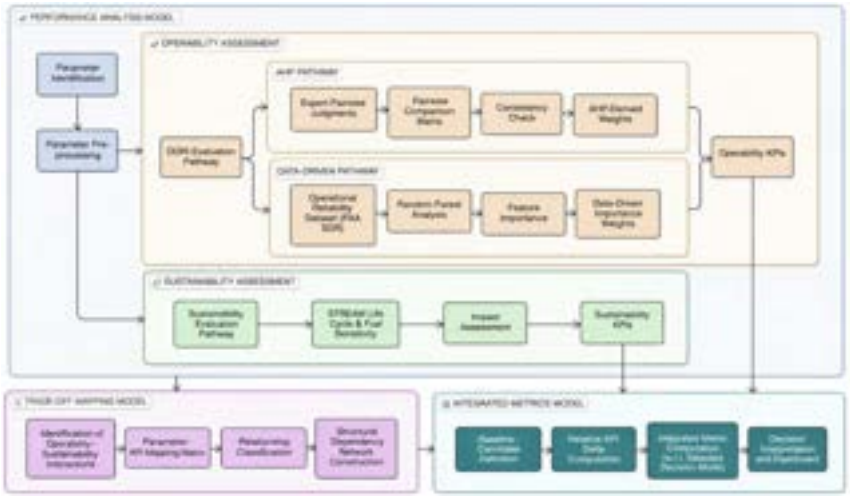


Figure 1. *Three-level architecture of the UMOS framework and overall workflow.*

3. Results / Conclusions

The principal contribution of this work is the Unified Model for Operability and Sustainability (UMOS), a subsystem-level framework integrating independent operability and sustainability quantification, structural dependency formalisation, and trade-off-oriented decision metrics.

The framework combines the Design-stage Operability Risk Index (DORI), a lifecycle-based CO_2 Intensity Index, and the trade-off metrics Sustainability Price of Operability (SPO) and Operability Price of Sustainability (OPS) within a unified assessment architecture. A Structural Dependency Network (SDN) is introduced to represent causal relationships between design attributes, maintenance drivers, operational parameters, and environmental indicators using typed-node and typed-link semantics. Application to the landing gear subsystem (ATA 32) included validation of the operability formulation using more than 15,000 FAA Service Difficulty Reports, supporting consistency between expert-derived weighting structures and operational maintenance data. The proposed framework provides a structured and traceable basis for subsystem-level sustainability-operability trade-off assessment during early aircraft design.

How can AI assist in Live Decision-Making for Aircraft Fleet Performance in Airlines Maintenance Control Centers?

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1. Introduction / Objectives

For a couple of years, the emergence of AI—and especially agentic AI technology—has opened up perspectives that the Aircraft Fleet Performance domain had been hoping for, for decades. Indeed, Maintenance Control Center (MCC) engineers make decisions in a few minutes based on dozens of complex input parameters such as pilot reports (PIREP), aircraft position, dispatch messages displayed in the cockpit, the results of onboard system diagnostics, and the availability of resources (mechanics, tools, spare parts), etc. These decisions are complex, time pressure is high, and human experience is key to choosing the right option that optimizes Fleet Performance. In a world where airlines face MCC engineers' shortage, this article will present some learnings from innovation works in real operational context, showing how AI assistance may facilitate the daily operations of MCC engineers, while maintaining Human Oversight on AI.

2. Methodology

Using a design-thinking approach, immersed at the AIRBUS Technical AOG Center (AIRTAC) where AIRBUS 24/7 engineers answer AOG technical requests from AIRBUS customers, we learnt about the opportunities in the user's journey when AI assistant can help to save time in the decision-making while assisting in checking all the parameters. We followed the EASA AI concepts to define the operational domain and to characterize the data in and out.
Then we focused on the assessment of the aircraft context, because this is the journey step where AI assistance is expected to bring the maximum value compared to operations without AI.
With the help of very experienced AIRTAC users, we modelled the functional agentic architecture of their human reasoning when they assess the aircraft context. It helped to identify the unitary agents and the key performance indicators for every agent, including the expected explanations that the AI assistant will provide with the outcome.
Then we prompted these specialized unitary agents with the end users, so that every word in the prompt is fully transparent and validated with the end users. From this functional architecture and unitary agents' prompts, the IT architects could draw up the optimized AI

agentic architecture, maximizing standard formats and common tools. We evaluated the architecture with a Functional Hazard Analysis supported by System Theoretic Process Analysis , making use of EASA AI concepts.
With the AI assistant prototype, we conducted a Test Campaign with many AIRTAC users in live and real conditions so that we verified that we always keep human oversight on AI, and we measured the performance, assessed the value, the comfort, trust and acceptance (as per EASA scale).
Single decisions on an aircraft may impact the full airline fleet operability. Saving time with AI assistance helps human users to balance the long-term sustainability of their decision. This is of highest importance when dispatchability is not sufficient, but also minimal fuel consumption and maximal flight performance also matter.



Figure 1. *Illustration of a MCC engineer assisted with Decision Helper AI while keeping human oversight on the decision.*

3. Results / Conclusions

With this work, we could experiment with an innovative approach of designing Fleet Performance applications with AI. Indeed, this is not about writing business requirements, not about writing user stories before agile software development, this is about architecturing and prompting AI agents with and by the end users directly. The performance and level of assistance is as the end users expect and accept it. As a consequence, we defined a new validation and verification method and new update method that ensure AI performance and human oversight at the right safe, sure and reliable level. In the article, we prove that time latency, recall and accuracy are not enough. Comfort, Trust, Acceptance, Assistance, Co2 and water footprint can be continuously balanced and tracked with respect to the assistance's real value to the end user and the impact on climate (Co2, water…).

Strategies for Technology Infrastructures in Aviation

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1. Introduction / Objectives

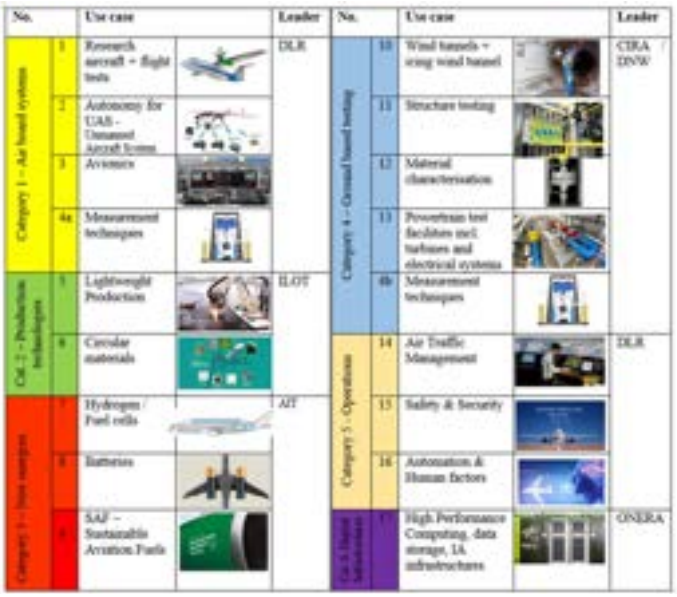
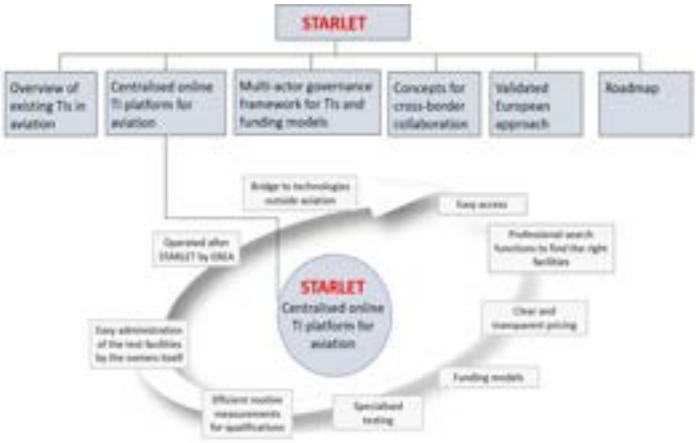


Figure 1. *Use cases for the Technology Infrastructures*

Aviation is undergoing a profound transformation driven by the urgent needs to decarbonize transport, strengthen resilience, and maintain global competitiveness. Major players worldwide are investing heavily in next-generation aviation technologies such as hydrogen and hybrid-electric propulsion, sustainable aviation fuels, AI-enabled design and optimization, and advanced lightweight materials. Achieving such future ambitions depends fundamentally on the availability, accessibility, and sustainable use of Technology Infrastructures (TIs). Yet, despite progress, the TI landscape remains fragmented with duplicated efforts, limited cross-border cooperation, and insufficient awareness among potential users regarding existing testing capabilities. The EU project STARLET addresses these challenges by developing coordinated, future-oriented strategies for the European aviation TI ecosystem. The project will map needs, gaps, and overlaps in the current European TIs landscape; propose innovative governance and funding models for both already existing and future TIs; and deliver a consolidated, web-based database of TIs with improved accessibility and functionality. By strengthening the coherence and long-term sustainability of TI's, STARLET aims to accelerate Europe's capacity to develop, validate and deploy the technologies required for climate-neutral aviation.

2. Methodology

TIs must remain at the forefront of innovation, providing capabilities required to validate emerging aviation technologies, but also supporting directly the EU aviation industry in the development of their programs and certification of their products. At the same time robust strategies are needed to ensure efficient operational processes and sustainable financial models. Reducing access barriers is essential - particularly for innovators like SME's and start-up that are driving technological breakthroughs. To support this ambition, and building on the use cases illustrated in Figure 1, the following objectives are defined:



- Map the European landscape of existing TIs related to aviation, including existing facilities, services, operating models, and typical users.
- Identify and understand the specific needs of current and prospective users, ranging from established industrial actors to SME's and start-ups, and conduct a gap analysis against the current state of the ecosystem.
- Develop improved and innovative strategic capabilities in aviation TI's, ensuring they are future-ready and aligned with sectoral transformation needs.
- Explore the feasibility and effectiveness of potentially relevant business and governance models, strategies and instruments for specific use cases (e.g. the development of disruptive technologies by start-ups or SME upscaling) to contributing to a coherent European approach to RTIs.
- Develop recommendations and a roadmap for upgraded and new TIs incl. concepts for governance, business, operating and funding models that facilitate broader and more equitable access to TIs.
- Strengthen knowledge continuity, relevance, and long-term value by enhancing the TI data platform and fostering transversal cooperation with other TI pilot initiatives.

The use cases addressed by STARLET reflect the multidisciplinary relevance of the topics in aviation and serve as a test bench to assess the effectiveness of the proposed approaches in achieving the objectives of the project.

3. Results / Conclusions

Figure 2 summarizes the main expected results of the STARLET project. The centralized database builds upon the already existing databases from EREA and IFAR and on previous work carried out in the framework of the RINGO EU Project. STARLET will extend this database, applying lessons learned in data management and stakeholder engagement, and involving experts from industry, research, and regulatory bodies through workshops, surveys, and interviews. These outcomes will improve the availability of availability and quality services for future technologies across the EU, enabling faster validation and deployment, and will have a lasting impact beyond the project's duration. The roadmap and recommendations will strengthen strategic planning at the EU and national levels, supporting environmental and societal objectives, and reinforcing Europe's global competitiveness. By promoting the more efficient, accessible, and sustainable use of TIs, STARLET will accelerate innovation, facilitate

faster market entry for breakthrough solutions, and help ensure that Europe remains a global leader in climate-neutral aviation.

Regional Operative Scenarios for Hybrid-Electric Regional Aircraft

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1. Introduction / Objectives

To reduce the greenhouse gas emissions of regional aviation, current research is focusing on the development of next-generation regional aircraft. In the HERA project , hybrid-electric aircraft with approximately 50 to 100 seats are studied with different propulsion system layouts. Although a lot of research has been conducted for the technology at aircraft level, key insights into how such concepts will be operated are missing.
In the current study, we examine how hybrid-electric regional aircraft can be deployed into airline networks. We study how these aircraft affect the high-level KPIs of an airline network, such as total profit and CO_2 emissions reduction, compared to kerosene-powered aircraft. In addition, it is key to understand how the introduction of this technology will impact the flight schedule, fleet composition, and energy consumption for varying missions in a regional network. This study allows to build regional operative scenarios for hybrid-electric aircraft.

2. Methodology

This study develops a computational framework which is schematically shown in Figure 1, consisting of a market deployment tool and a flight physics model to analyze the flight performance under varying mission requirements.

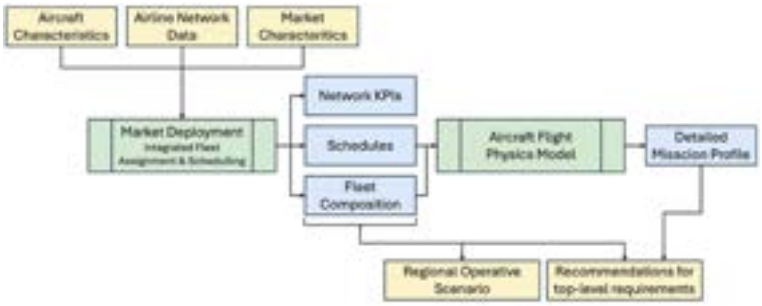


Figure 1. *Overview of the computational framework*

The market deployment tool, based on , integrates fleet assignment and scheduling to model airline decision making. Although the decision making is driven by the overall profit, the impact on CO_2 emissions is closely monitored. The tool produces an optimal fleet assignment through a dynamic programming formulation, considering aircraft characteristics, such as speed, maximum range, capacity, and turnaround time, as well as

network requirements specified as passenger demand between origin-destination pairs. The missions in the output schedule are then provided as inputs to a Siemens Simcenter Amesim model which simulates the flight physics behavior of the aircraft. This model considers the powerplant, flight dynamics, and control of the hybrid-electric aircraft, to allow for multiple off-design mission analyses covering the network.
The output of these flight performance models can be used to propose new top-level requirements, in terms of payload and range, to design hybrid-electric aircraft which are better suited to the operational demands of the considered airline(s). Information visualization serves as a powerful tool for conveying knowledge efficiently and enabling interacting with data in meaningful ways.

3. Results / Conclusions

The results will focus on the changes in networks KPIs and fleet characteristics when novel hybrid-electric aircraft are introduced in the market, compared to kerosene-powered alternatives. It is key to understand how the schedules and fleet composition change as result of different range and flight performance capabilities. We consider two airline networks; first, we formulate a case study based on a hub-and-spoke network, where passengers transfer at the hub and the regional or short-range flights often act as "feeders" to connect passenger to long-haul routes. Second, we consider a regional point-to-point network providing direct connections.
Comparison of these two business models helps formulating recommendations for future operative scenarios. These scenarios and the rationale behind the market deployment will be presented in a visual way to inform various stakeholders on the opportunities and bottlenecks of future hybrid-electric regional aircraft.

Acknowledgement: The research presented in this paper has been performed in the framework of the HERA project (Hybrid Electric Regional Aircraft) and has received funding from the European Union Clean Aviation Program under grant agreement n°101102007.

Reducing fuel flow and CO_2 emissions during cruise flight through continuously increasing altitude operations on the North Atlantic Track System

Marco-Michael Temme, Metodi Meissner
DLR – German Aerospace Center

1. Introduction

The objective of this study is to estimate the potential environmental benefit of Continuously Increasing Altitude Operations (CIAO) allowing for continuous, individual flight altitude adjustment to minimize fuel consumption on a weight-dependent basis assuming no significant impact on airspace capacity. As a result of global warming, reducing fuel consumption and CO_2 emissions has become a significant societal challenge in the aviation industry as well. In civil aviation, flights are generally routed along the great circle distance to minimize the overall flight length. In order to minimize energy requirements, it is imperative to take into account weather conditions such as air currents and potential headwinds. Furthermore, altitudes are methodically adjusted, typically through one or two step climbs, in

order to align with the aircraft's current weight as a consequence of ongoing mass reduction due to fuel consumption.

2. Methodology

The reduction in aircraft weight considered in this study is directly dependent on fuel consumption [Iken 2022]. In order to follow individually optimized trajectories, pilots and airlines require flexibility regarding airspeed, altitude, and routing. However, airspace capacity constraints can significantly limit this flexibility. For the purposes of this study, the airspace over the Atlantic was analyzed using the North Atlantic Track System (NATS), whose routes are set twice a day and run predominantly in parallel and, over long stretches, without direct radar surveillance [ICAO 2021]. Within the NATS, each aircraft is assigned fixed flight routes and altitudes, from which they can generally only deviate in the controlled sections – typically by climbing higher – to account for the reduced aircraft weight resulting from fuel consumption.

By adjusting flight paths and reducing vertical separation, it would be possible to eliminate fixed altitude guidelines without a loss of capacity, allowing all aircraft to fly at individual altitudes over longer distances [Sedehi 2021]. Using data from various Flight Crew Operations Manuals (FCOM), the weight-dependent optimal flight altitudes were incorporated into mathematical models that allow for a fuel flow-dependent calculation of the respective optimal flight altitude while simultaneously estimating fuel consumption (Figure 1) (for example [Airbus 2004]). In this way, the altitudes of original flight paths could be retroactively adjusted in a simulation so that each aircraft could always fly at its fuel-efficient optimal altitude during transatlantic flights. By applying the same fuel consumption calculation methods, it is possible to compare different flight paths with varying step climbs as well as continuous climbs, thereby identifying potential fuel savings. By applying this to current traffic scenarios, it becomes possible to estimate potential kerosene savings for an entire airspace as well as potential CO_2 reductions over various time periods.

In order to ensure the trajectory optimization remained realistic, all aircraft simulated in the CIAO procedure were introduced into airspace at their actual optimal altitude and were subsequently released at their optimal altitude at the moment of leaving the considered sector. The adjustment therefore always applied exclusively to the altitudes.

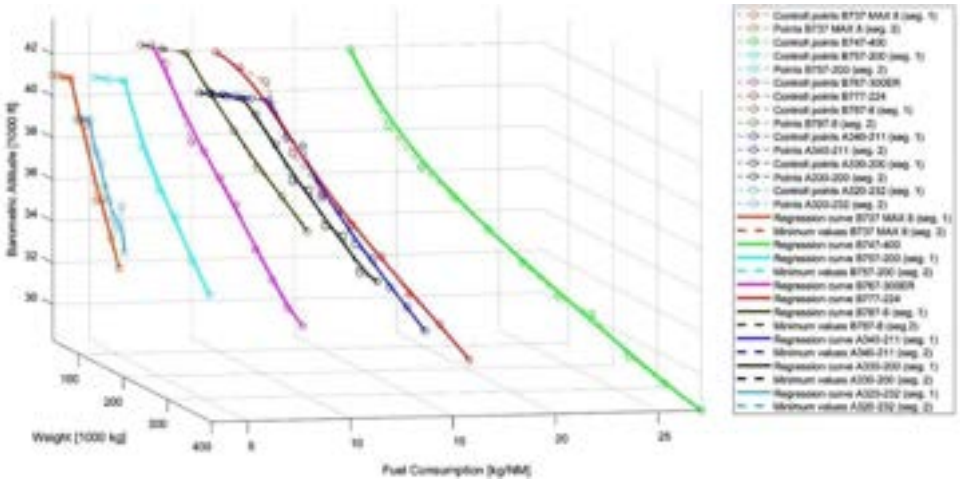


Figure 1. *Interpolation of altitude dependent fuel flows for nine aircraft.*

3. Results

Initial analyses have shown that the results mainly depend on the assumed aircraft load-factor, number of step climbs, and aircraft types. The results show that fuel savings ranging from 0.63% to just under 1.35% are possible on North Atlantic routes. For a single flight, this can result in a fuel savings of up to 850 kg, which also translates to a reduction in CO_2 emissions of over 2.6 tons. A sensitivity analysis has shown that the greatest source of uncertainty in this model is the estimate of the initial cruise-flight aircraft weight which is assumed based on the highest cruise-flight level in the original flight trajectory. It also became apparent that, while the step climbs flown were often close to the optimal altitude at the start of the route, they almost always remained below the optimal altitude as the flight progressed.

Reliability-Based Maintenance Cost Estimation for Alternative-Propulsion Aircraft

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[2] Boeing Deutschland GmbH, Germany

1. Introduction / Objectives

Maintenance cost is a significant contributor to aircraft direct operating cost and is well established for conventional aircraft through empirical methods such as AEA, ATA-DMC, DLR and Scholz-based correlations. These methods are calibrated using decades of turbofan and turboprop operational data, but their direct application to alternative-propulsion aircraft is limited. Battery-electric, hydrogen fuel-cell and liquid-hydrogen aircraft introduce new architectures, life-limited components and safety-critical subsystems for which mature maintenance datasets are not yet available. Maintenance cost is an important determinant of the economic viability of alternative-propulsion aircraft may therefore be driven not only by conventional stochastic engine events, but also by scheduled replacement of batteries, fuel-cell stacks, cryogenic tanks, compressors, electric motors, high-voltage systems and hydrogen-handling components. This paper proposes a hybrid maintenance-cost framework combining ATA-2003 parametric estimation, Weibull component reliability and Bayesian fusion to estimate scheduled and unscheduled maintenance cost per flight hour for alternative-propulsion aircraft.

2. Methodology

The proposed framework estimates maintenance cost per flight hour using a hybrid parametric–reliability structure. For conventional aircraft, the airframe and engine maintenance baselines are modelled based on the ATA-2003-style parametric maintenance man-hour relations. For alternative-propulsion aircraft, where mature operational maintenance data are not yet available, maintenance cost is modelled through component-level scheduled replacement, inspection tasks and unscheduled corrective events. The propulsion-specific component contribution is evaluated using a Weibull reliability model:

$$R_i(t) = \exp\left[-\left(\frac{t-\gamma_i}{\eta_{\text{eff},i}}\right)^{\beta_i}\right],$$

where $R_i(t)$ is the reliability of component i at time t, β_i is the Weibull shape parameter, γ_i is the location parameter, and $\eta_{eff,i}$is the environmentally adjusted characteristic life. Similarly, the probability of unscheduled corrective maintenance is estimated using a conditional Weibull failure probability:

$$P(\text{failure probability}) = 1 - \frac{R_i(t_a + t_b)}{R_i(t_a)}$$

where t_a is the accumulated component age and t_b is the mission block time. This allows the model to account for component ageing and wear-out effects during each flight.

The overall Maintenance cost per flight hour is modelled as:

$$C_{mx,FH} = C_{AF,FH} + K_{TRL}(C_{Sche\ ,FH} + C_{Insp,FH} + C_{Unsched,FH}) + C_{LLP,FH}$$

where $C_{mx,FH}$ is the total maintenance cost per flight hour, $C_{AF,FH}$ is the ATA-2003 airframe maintenance cost, $C_{Sch\ \ ,FH}$ is the scheduled replacement cost of life-limited components, $C_{Insp,FH}$ is the inspection cost, $C_{Unsched,FH}$ is the expected corrective maintenance cost, $C_{LLP,FH}$ is the engine life-limited-part and shop-visit reserve, and K_{TRL}represents technology-readiness and learning effects.

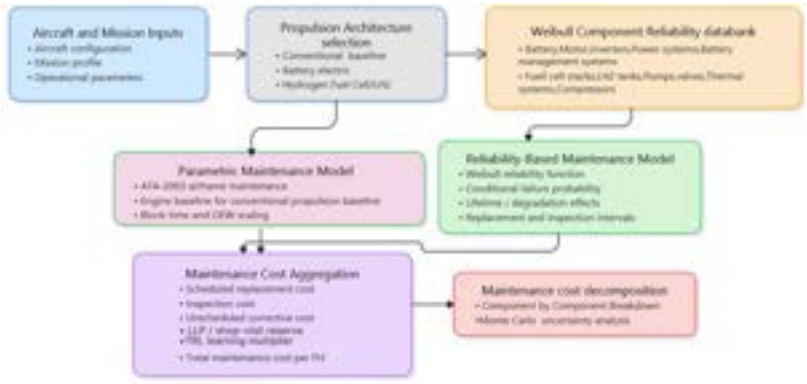


Figure 1 *.Maintenance-cost estimation workflow linking aircraft and mission inputs, propulsion architecture selection, ATA-2003 parametric maintenance, Weibull component reliability modelling, scheduled and unscheduled cost aggregation, maintenance cost decomposition and uncertainty analysis*

3. Results / Conclusions

A 19-seat regional-aircraft case study was evaluated for a 300 km mission, comparing two conventional turboprops, one battery-electric concept and one hydrogen fuel-cell concept. Using aircraft-specific trajectory-derived block times, the conventional baselines give BAe Jetstream 31($190/FH and $698/flight) and Beechcraft 1900D ($215/FH and $692/flight). The

reliability-based estimates give Heart ES-19 ($231/FH and $346/flight) and Do228-ZA600 ($189/FH and $297/flight) for the hydrogen fuel-cell concept under assumed component life and cost. Component-level decomposition shows that scheduled maintenance dominates across all propulsion types. The battery subsystem accounts for 68% of electric propulsion maintenance, while the fuel-cell subsystem accounts for 75% of hydrogen maintenance Cost. A 2,000-cycle ageing sensitivity increases hydrogen and electric maintenance costs by 15% and 14%, respectively. Distance sensitivity shows that electric maintenance cost becomes the highest as mission distance increases, while hydrogen remains lower than electric but above the conventional turboprop baselines.

Using Continuous-Time Markov Chains for Model-Based Safety Analysis

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1. Introduction / Objectives

Fault tree analysis (FTA), Markov analysis (MA) and model-based safety analysis (MBSA) are methods recommended by aerospace standards to support safety assessment of complex technical systems. FTA remains the dominant industrial approach because it is the simplest and the most effective method. However, it often produces conservative estimates and relies on ad hoc correction formulas to handle dynamic models. MA provides dynamic representation and exact calculation, but the model representation is cumbersome. MBSA is gaining interest in safety engineering because it supports versatile and efficient representation of failure propagation in complex systems. Moreover, MBSA implementation, like AltaRica , features model subclasses that can be compiled into fault trees or Markov chains.
This paper presents a novel MBSA-to-Markov compilation and computation chain (GEMSEO-MBSA, based on GEMSEO®), accompanied by experiments designed to validate the approach and to assess its effectiveness. It also compares FTA and MA on two benchmark problems of increasing complexity.

2. Methodology

AltaRica is a high-level modelling language that supports MBSA and enables efficient modelling of complex technical systems using libraries of reusable components and modelling patterns . Different assessment tools are available for AltaRica models: Boolean equations generation, sequence generation, Markov chain generation, and stochastic simulation . The existing tools provide a baseline to compute causes of events and quantify their probability of occurrence.
We have been developed GEMSEO-MBSA, an AltaRica-free MA tool based on the open-source Python library GEMSEO® . It models a use case using a set of elementary blocks and transition rules, and generates all possible sequences leading to undesired states. It can validate these sequences against those generated by native AltaRica tools. Then, it derives the continuous-time Markov chain (CTMC) and computes the exact probability of each state. It can therefore handle order-dependent failures, latent failures, and complex reconfiguration sequences in a mathematically rigorous framework, under the assumption that all failure rates follow exponential distributions. It also enables the study of the impact of

uncertainty in failure rates on the probability of undesired events through the computation of sensitivity indices and importance factors obtained by analytical differentiation of the Kolmogorov equations.
We therefore propose to use GEMSEO-MBSA to model the study cases and assess the benefits and limitations of the approach. Two AltaRica models provide reference study cases. A command/monitoring architecture (see Figure 1) offers a controlled setting in which FTA and MA results can be directly contrasted; this example illustrates order-dependent failures, latent failures, and reconfiguration sequences. The BSCU model from then demonstrates the scalability of the approach to an industrial-scale safety model.

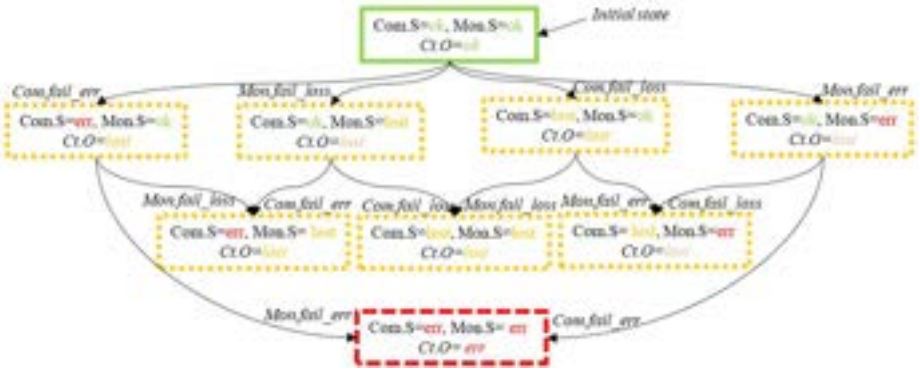


Figure 1. CTMC of a command/monitoring architecture.

3. Results / Conclusions

The proposed method demonstrates how MA quantification can be applied to AltaRica models satisfying the Markovian hypothesis.
The experiment supported the validation of the new tool chain GEMSEO-MBSA. Probability estimates on the CTMC were compared against fault-tree estimations adapted per to account for latent failures and event sequence ordering. This constitutes a validation step of both the accuracy and tractability of the undesired-event quantification with GEMSEO-MBSA. Additional functionalities have been developed and are currently under testing: sensitivity analysis and the computation of standard importance factors.
Furthermore, since GEMSEO MBSA provides exact probability estimates, the experiment also enables the assessment of the accuracy of other quantification methods currently applied to AltaRica models.

Management of Command-and-Control Link Loss for Automated VCA Flight in Uncontrolled Airspace

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1. Introduction

Most unmanned aircraft systems (UAS) today are operated within a close distance of the

Remote Pilot (RP), using a direct radio link for command and control (C2). The C2 link loss (C2LL) could result in the RP no longer being able to manage the UAS flight . This is a known vulnerability of current radio links and there are methods in place to mitigate and manage the UAS in such a contingency situation, for example: redundancy of communication links, or fail-safe modes automatically triggered by the loss of C2 signal, without the need for a human input. Typically, the UAS would perform one of the following actions: return to home, hover on the spot, or land, or a combination of those . In the scope of SESAR OPERA project, this paper discusses a case of the defined C2LL processes for an automatic Vertical Take-Off and Landing Capable Aircraft (VCA) operating in low complexity uncontrolled airspace environment. This case focuses on the C2LL occurrence and the processes of the possible outcome from C2LL phases. The defined C2LL processes involve several actors and systems participating in the planning and execution of a VCA flight – the automatic VCA (virtual aircraft NUUVA V300), Remote Pilots (RP1 and RP2), Ground Control Stations (GCS1 and GSC2), UAS Operator (UASO) operation center (OC), Flight Information Services Officer (FISO).

2. Methodology

The C2LL management and procedures in case of a VCA flight in uncontrolled airspace present a very complex task that requires the synchronization of operating actions assigned to different entities involved in flight planning and execution .

Applied methodology aims at decomposing the process of each phase in the C2LL into actions of actors and identifying the success and failure end states. This process is built around the VCA flight trajectory programme which controls the aircraft. Therefore, the C2LL process defined in OperA presents the sequence of action steps along the phases of this process. Each phase contains several steps (subsequent, or parallel) that describe the action, the initiating and the receiving actor.

There are four C2LL phases: C2LL identification, link re-establishment, RP2 engagement and takeover, and execution of contingency procedure. An overall C2LL process can be algorithmically described as a cascade failure approach, meaning that each phase after C2LL identification is followed by a subsequent phase, if not successfully completed.

The C2LL identification starts with VCA indicating C2LL by automatic setting of the 7400-squawk code thus notifying the RP and FISO. The VCA flight trajectory programme continues the flight toward the next programmed way point. 7400-squawk code triggers the RP to perform all necessary checks in GCS, informs the UASO and reports to FISO on the potential contingency situation and flight intent. FISO provides any relevant information to RP and the affected other airspace users in the AOR. OC confirms the contingency procedure and provides an advisory to RP1 and a notification to RP2. Finally, GCS provides information about the contingency trajectory to RP in case the C2L is not re-established.

When the link is re-established, this is notified to RP, who reports to FISO and informs UASO OC. The failure end state of this case triggers the next use case – activation of RPS2.

The RP2 engagement is performed by UASO OC. The OC engages RP2 by providing all available information and advisories to RP2 to take control of the VCA. The success end state of this case is establishing control on the VCA and continuation of the mission as planned.

The failure end state triggers the use case of execution of contingency trajectory to land the VCA on a pre-defined safety landing site. RP reports to FISO on the expected route and flight profile of the VCA, as well as the predefined landing site. In parallel the UASO acts according to the procedure in ERP. The success end state of this case is the safe landing on the

predefined place, and the failure end state is the escalation to the emergency situation, landing at not pre-defined location, or aircraft crash.

3. Results / Conclusions

The outcome of C2LL case in OperA project demonstrates management of such situation tailored around the design of NUUVA V300 automatic VCA. While such process may be different for other aerial vehicles, the presented use cases give an example of approach to the management of C2LL and demonstrate practical actions. In the validation scope of OPERA project, the results of C2LL study case within uncontrolled airspace were obtained by the human-in-the-loop real time simulations (RTS) . C2LL was executed based on defined procedures and the simulated process in simulation was completed successfully both by the human and system entities. The first C2LL event simulated recovery and flight continued via route; the second event resulted in landing at the predefined alternate site. During the RTS, none of the participating human actors (RPs, FISOs, OC staff) provided any negative observations. The code 7400 was transmitted by UAS just after it lost C2 link and recognized on HMI screen; with undue delay, ATS staff (FISO) was connected via dedicated line with OC (VCA operator and RP); predefined contingency procedure was executed within safety margins; the contingency trajectories (holding patterns, fixes, turns and operating altitudes) were built on VCA specific routes previously validated in several operational scenarios; other airspace users were timely informed. The contingency process was feasible and completed successfully in the exercised scope. Participating experts assessed the outcome as positive and relevant to the defined concept.

Aerodynamic/Aeroelastic Analysis

Chaired by:
Mr. Pietro Roncioni (CIRA, Italy)

Aerodynamic Characterization of HYPERION Suborbital Spaceplane

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[2]DAC, Italy
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1. Introduction / Objectives

The HYPERION (Suborbital HYPERsonic Spaceplane capable to support payload In Orbit iNsertion) project, coordinated by Campania Aerospace District (DAC), was focused on feasibility assessment and development and preliminary design of a suborbital spaceplane allowing the extension of air defense capacity (Intelligence, Surveillance, Reconnaissance and Interception) above the present 20 km limit, against recent hypersonic threats. Its multi-

capacity includes early warning and payload (micro-satellites) air-launch to Low Earth Orbit (LEO).
The scientific and technological research activity was co-financed by the Ministry of Defense within the framework of the National Military Research Plan (PNRM) managed by the General Secretariat of Defense (SGD) and the National Armaments Directorate (DNA).
As high-level requirements, HYPERION is thought to be a 6-seat, single-stage small spaceplane (25m length, 16m wingspan and with 31-ton MTOW) capable to takeoff and landing from/to a runway of 1 km, cruising at Mach=4.5 and stratospheric altitude propelled by a turbo-ramjet engine, to have a downrange of 7000 km in two hours, and capable to ascend to about 100 km altitude (von Karman line) by using a cluster of hybrid rocket engines.
The HYPERION top-level mission requirements include: i) routine, fast and wide reconnaissance over the national territory and extended air space; ii) emergency quick-response interception of unidentified high-speed systems; iii) fast long-range transportation and ISR for missions outside the national territory; and iv) flexible, fast and cheap microsatellite-size payload air-launch into LEO.

2. Methodology

The present paper describes in detail the main achievements of the aerodynamic analysis of the HYPERION project. The numerical and experimental aerodynamic activities, performed by different partners along the development of HYPERION project, have been mainly focused on: 1) Generation of the aerodynamic database (AEDB) of HYPERION nominal configuration 4.0, including the evaluation of viscous, rarefaction and elevator's deflection effects with engineering methods (and with a few CFD-bases results verification); 2)Experimental aerodynamic test campaign in CIRA-PT1 wind tunnel; 3) Experimental aerodynamic test campaign in INCAS trisonic wind tunnel; 4) CFD simulations campaign to support experimental wind tunnel campaigns in CIRA e INCAS for the elaboration of sting, cavity effects corrections, and for the extrapolation to flight process of measured data (i.e., effect of Reynolds number).

3. Results / Conclusions

Figure 1-left shows the HYPERION model (1:72 scale) installed in the CIRA-PT1 test chamber. The model is also equipped by two flow-through nacelles by simulating the two engines mounted aside the rear fuselage and over the delta wing, and was designed and realized in a modular way, meaning that it is possible to install inside the model both CIRA and INCAS force/moment balances by using properly designed adaptors and balance sleeves.

Figure 1-right reports the distribution of the lift coefficients, measured by CIRA and INCAS, as a function of the Mach number at different angles of attack (0-deg and 6-deg). The good comparison with the aerodynamic database and CFD simulations performed in wind tunnel conditions is also clearly highlighted.



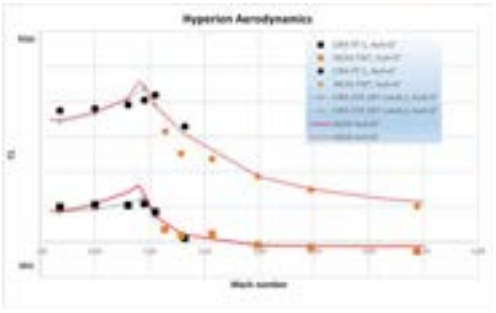


Figure 1. Hyperion wind tunnel model in CIRA PT1 (left) and Experimental/numerical comparison of lift coefficient results.

The full paper will describe in detail all the steps of aerodynamic analyses, which have provided data for flight mechanics analysis and trajectories generation, and for thermo-structural analysis of full spaceplane configuration and for the design of different demonstrators (wind tunnel scaled model, radome model, wing leading edge models, intake with ramjet duct model) used to increase the design confidence and reliability.

Analysis of Critical Stores in an Internal Weapons Bay Using Detached Eddy Simulations

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1. Introduction / Objectives

Modern fighter aircraft design configurations have trended towards the use of internal weapons bays due to an emphasis on low observability. However, the interaction between the freestream flow and the open internal bay creates a shear layer which induces a pressure gradient along the cavity floor resulting in pitch up moments and unsteady forces on stores, potentially creating unsafe store separation scenario.
Previous studies have focused on the effects of a given store geometry in the bay, various bay configurations, or the aeroacoustics effects. This study aims to quantify the effects of various store sizes in a prescribed internal weapons bay geometry to determine which store size is critical, defined as the store size with the greatest pitch-up moment during carriage. Results have the potential to reduce flight testing requirements, thus saving time and costs during store separation certification.

2. Methodology

In order to validate Computational Fluid Dynamics' (CFD's) capability to simulate the complex flow interactions of an internal weapons bay, a NASA wind tunnel experiment was recreated and simulated in Star-CCM+ using Detached Eddy Simulations (DES) with Spalart-Allmaras (S-A) turbulence modelling with a time-step of $1x10^{-4}$s for a total of 0.5s of flow time. The NASA cavity model has a Length-to-Depth (L/D) ratio and a Length-to-Width (L/W) ratio of 4.375. The atmospheric conditions and resultant cavity coefficients of pressure were taken from run 15 of NASA's experiment, which was at Mach 0.85, total pressure of 14.724psi, total temperature of 116.9°F, and a Reynolds number of 4.0×10^{6}/ft. Mesh refinement was used on the leading edge of the model forwards of the cavity, as well as in and above the cavity

itself. Upon completion of the validation study, it was determined that cavity flows could be adequately numerically simulated. An example from this grid convergence is shown in Figure 1, which depicts the density gradient magnitude and shows the shear layer spanning the cavity lid, impinging on the aft wall, and the recirculation inside the cavity.
This validated CFD capability is used with a 1/33 scale model inspired by modern fighter jet designs was created with a L/D ratio of 5, and a L/W ratio of 4, which was chosen to accommodate future wind tunnel testing. To simulate this model, the same validated conditions were applied, except for the total pressure and temperature which were set to standard atmospheric conditions at sea level. Grid convergence was conducted on this model, with similar mesh refinement areas, and subsequently, store bodies, inspired by typical air-to-ground munitions, were placed inside the weapons bay and simulated at the same conditions. Three store models were inspired by 2000lb, 1000lb, and 500lb class bombs [5, 6], with lengths of 4.675in, 3.619in, and 2.805in respectively and a finesse ratio of around 8.5. The forces and moments on these stores were determined and compared to evaluate the store with the greatest pitch-up moment, indicating the critical store where unsafe store separation is most likely.

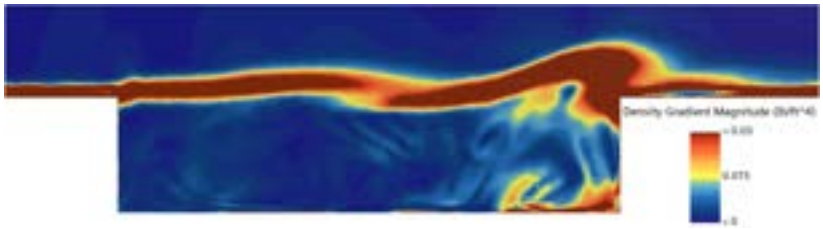


Figure 1. *Density gradient magnitude inside NASA cavity model using DES with S-A turbulence, flow from left to right.*

3. Results / Conclusions

DES with S-A turbulence modelling was verified to adequately model cavity flow interactions and the 500lb-like bomb model was determined to be the critical store. The smallest of the stores shows less interaction with the shear layer and occupies less cross-sectional area in the bay, which reduces both the store's impact on shear layer stability and the pressure feedback mechanism inside the cavity. This results in a greater pressure gradient along the cavity floor and thus a greater pitch-up moment induced on the store.
By identifying smaller classes of stores as the ones most likely to encounter unsafe release conditions, store separation flight test campaigns can focus on these classes of stores and may conduct partial "certification by analogy" for larger store classes. This can subsequently reduce the required number of test flights and/or store releases during the certification process, thus decreasing both the time and costs required for certification.

Experimental Research of Cantilever Wing Flutter and Its Suppression Algorithm at Low Reynolds Numbers Based on Unsteady VLM Modeling

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1. Introduction / Objectives

Flutter has been extensively studied at moderate and high Reynolds numbers. However, research at Reynolds numbers below 100,000 remains limited, with only a few studies focusing on flutter suppression at this scale. As the use of UAVs continues to grow, the demand for further research in this area is becoming increasingly important. This paper aims to experimentally investigate flutter on a flexible cantilever wing at low Reynolds numbers, to evaluate the possibility of actively damping or suppressing flutter using an aileron controlled by a real-time algorithm.

2. Methodology

To perform experimental research a 230 mm half-span wing model (Figure 1.) is designed and manufactured based on Pazy wing design. It features a solid 0.5 mm thick spring steel spar as the primary load-bearing element, along with multiple ribs and additional components manufactured from 3D-printed PCTG plastic. At the tip section, an additional structure is attached, housing a MEMS-type accelerometer/gyroscope and a digital servo. A 80 mm long aileron with a compliant hinge is attached to the structure. The chordwise aileron size is 30% of the chord. To reduce the torsional frequency of the wing, a steel rod with weights is placed at the tip.
Initially wing modal tests and flutter tests in the wind tunnel were performed with the aileron rigidly fixed at the 0° deflection angle. The vibrations and the tip displacements were measured from 0° to 8° angle of attack every 2 degrees. The tests were performed up to the flutter speed at each angle of attack. Displacement was measured externally at the wing tip with a laser triangulation sensor. The same sensor was also used to acquire additional vibration data to verify the readings from the main accelerometer mounted inside the wing. Additionally, strain gauges were mounted on the wing root to acquire strain data.

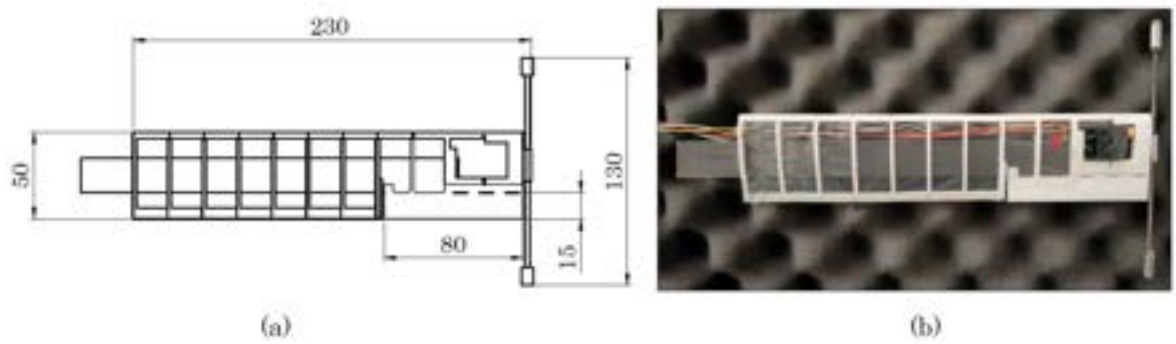


Figure 1. *Experimental wing: a) wing dimensions in millimeters; b) manufactured wing for tests in the wind tunnel*

A digital twin was developed using the modeled wing and was calibrated based on the acquired experimental data. An algorithm for predicting control requirements to suppress wing flutter was developed using an in-house fast unsteady vortex lattice method (UVLM) coupled with a nonlinear structural model. The algorithm introduces phase-advanced aerodynamic damping through aileron actuation. It determines control inputs based on the measured wing state from embedded sensors and commands aileron deflections to generate aerodynamic loads out of phase with the structural oscillations, thereby increasing effective damping and mitigating flutter. Due to the highly nonlinear flow behavior at low Reynolds numbers, additional aerodynamic and phase-lag compensation terms are included and calibrated using experimental data.

3. Results / Conclusions

The experimental tests showed good agreement with the digital twin model, and after calibration, the UVLM algorithm was able to capture the flutter behavior. The flutter prediction was closest at a low angle of attack and diverged more at higher angles, confirming that aerodynamic predictions with the UVLM are less accurate when flow separation happens. Finally, the proposed aeroelastic control algorithm demonstrated the potential to delay the flutter onset. Overall, these results offer a promising framework for active flutter suppression at low Reynolds numbers.

Evaluating metamaterials for aeroelastic instability mitigation in wind energy

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1. Introduction / Objectives

Aeroelastic instabilities, such as vortex-induced vibrations (VIV), pose significant structural risks to slender aerospace components. This includes high aspect ratio wings, helicopter rotors and turbomachinery blades under stalled conditions. This work proposes the use of Locally Resonant Metamaterials (LRM) as a passive, aerodynamically transparent mitigation strategy. LRMs leverage periodic arrays of lightweight resonators (integrated via surface microstructures or embedded lattice cells) to dynamically absorb and counteract external aerodynamic forcing without altering the airfoil geometry. The primary objective is to evaluate the feasibility of LRMs to suppress large amplitude vibrations in an airfoil operating under high angles of attack. By exploring these fundamental aeroelastic mechanisms, this study establishes a foundation for lightweight vibration suppression applicable to both advanced aviation configurations and related fields such as next generation wind energy systems.

2. Methodology

To evaluate this approach, the problem is cast into a classical symmetric airfoil (NACA 0021) elastically mounted in a 2D transverse oscillation setup. This setup serves as a representative

baseline for deep stall aeroelastic phenomena common to aircraft profiles at extreme angles of attack (90°) and bluff aerospace structures. A numerical model is developed using the open source finite volume computational fluid dynamics (CFD) package *OpenFOAM*. The framework solves the incompressible Navier Stokes equations utilizing an arbitrary Lagrangian Eulerian (ALE) formulation to handle grid deformation.
Turbulence modeling is conducted via an unsteady Reynolds-Averaged Navier Stokes (URANS) approach using the k-omega SST model with a wall-resolved mesh (y+<1). A partitioned fluid-structure interaction (FSI) strategy is deployed, where the baseline rigid body motion solver is extended through a tailored development to couple the dynamics of an internal resonator into the main system. The performance of the resonator is comprehensively parameterized based on its natural frequency and its relative mass ratio with respect to the airfoil. Through this coupled FSI framework, the non linear aerodynamic loads are tracked alongside the structural response, allowing us to investigate how the internal resonator influences the underlying aeroelastic lock-in mechanisms under highly separated flow conditions.

3. Results / Conclusions

The results demonstrate that the introduction of an internal resonator creates an aeroelastic frequency bifurcation, which effectively suppresses system lock-in by shifting structural frequencies away from the natural flow shedding frequency. A distinct frequency bandgap is identified where vibration amplitudes are significantly mitigated.
However, parametric analysis reveals that the mitigation efficiency is strongly governed by the mass of the resonator. For realistic, lightweight configurations suitable for aviation design, amplitude attenuation remains limited. In particular, achieving a 50% reduction in vibration amplitude requires a mass ratio exceeding 0.25. These findings demonstrate that while frequency bifurcation is a viable passive mechanism for suppressing flow induced vibrations in airfoils, alternative metamaterial configurations must be targeted to satisfy the strict lightweight constraints of aerospace applications.

Flutter Analysis of Flexible Wing Configurations Using Pre-Stressed Structures Technique

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1. Introduction / Objectives

One of the objectives of the European project EXAELIA (EXperimental Aircraft for European Leadership In Aviation) launched in the frame of the Horizon Europe Program is to develop new computation techniques to be implemented in Future Long Range Aircraft (FLRA).
The goal of this work is to define an improved methodology of flutter effect computing by taking into consideration the pre-stressed effect at a high deformed structure.
This paper also intends to present a comparison between typical way of flutter computation and the way where the pre-stressed structure effect is taking in consideration.

2. Methodology

Starting from the MSC Nastran methodology in both nonlinear structural/modal and aero elasticity/flutter analysis, the paper intends to develop and present the way of transferring computational data from one analysis type to the other.
By defining this computing implementation and methodology, it will be possible to observe the geometrical nonlinearities effect on flutter stability at flexible wings.
The great opportunity is that that the implementation of the above described technique will be made on EXAELIA wing models of small scale demonstrators that are planned to be tested in the wind tunnel. This way the experimental results may be compared with the theoretical computed one.

3. Results / Conclusions

As a conclusion the paper intends to develop a flutter computing technique based on nonlinear deformed and stressed structures. The model to be used is developed and tested in EXAELIA project.

Development and Numerical Investigation of Dimple Surfaces for Flow Loss Reduction on Gear Side Faces

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1. Introduction

Flow power losses in gear systems represent a significant source of efficiency reduction, particularly at high rotational speeds. Surface texturing has been shown to influence flow behavior in various engineering applications, however its effect on gear side faces remains insufficiently explored.

This study investigates the impact of dimpled surface structures on the lateral faces of gears compared to smooth surfaces. The objective is to evaluate whether such surface modifications can reduce flow-induced losses.
A numerical approach based on computational fluid dynamics (CFD) is applied to analyze the influence of dimple geometry on flow characteristics and torque induced by the surface. The work aims to identify optimal geometric parameters, including dimple size, depth, and distribution, thereby contributing to the advancement of surface engineering strategies in gear design.

2. Methodology

The investigation is conducted using CFD simulations with Simerics MP+ to model fluid flow over a rotating disc with smooth and dimpled lateral surfaces. Simulations are performed for both configurations under varying rotational speeds and axial clearances to evaluate their influence on flow characteristics and drag-related losses. The dimple parameters, including diameter, depth, spacing, and arrangement, are systematically varied to enable a parametric analysis.
All simulations are performed under consistent boundary conditions to ensure comparability. The computational mesh, including the dimple geometry, is generated using a custom

mathematical script to avoid numerical artifacts and unintended surface features. A refined near-wall mesh is applied in the dimple region, following the contour of the surface to accurately resolve flow structures influenced by the texturing.
The results are evaluated with respect to key fluid dynamic quantities such as flow separation, turbulence intensity, pressure distribution, and drag forces. The influence of dimple geometry on these parameters is assessed through a comparative analysis between smooth and structured surfaces.
The methodology focuses on isolating the effects of surface structuring and quantifying performance improvements.
The numerical results are further examined for physical consistency and compared with established findings in the fields of fluid dynamics and surface texturing. This approach enables a systematic assessment of the effectiveness of dimpled surfaces in gear applications.

3. Results

Overall, this approach allows for a detailed investigation of the underlying physical mechanisms and provides a robust basis for evaluating the effectiveness of dimpled surfaces in gear applications.
The results of this study are expected to demonstrate that dimpled surface structures can positively influence the flow behavior around gear side faces by reducing flow separation and drag-related losses. Certain dimple geometries are anticipated to promote more stable flow patterns and lower turbulence intensity, leading to improved efficiency.
In conclusion, the study provides valuable insights into the interaction between structured surfaces and fluid flow, offering a foundation for further experimental investigations and practical implementation. The results may contribute to the development of more efficient gear systems.

Flight Dynamics Assessment of a Twin-Fuselage Aircraft Using a Conceptual-Level Aerodynamics Model

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1. Introduction / Objectives

Since the early days of commercial aviation, conventional Tube-and-Wing configurations have remained the dominant architecture, reaching a high level of technological maturity where further gains in fuel efficiency and emissions reduction require increasingly complex incremental improvements. In this context, unconventional aircraft configurations have emerged as promising alternatives to achieve substantial improvements.
Among them, Twin-Fuselage configurations remain comparatively unexplored, particularly in terms of their flight dynamics and handling qualities. Deviations from the conventional wing–fuselage–empennage layout can significantly alter stability and controllability characteristics, requiring dedicated assessment at early design stages.
This work aims to address this gap by providing a comprehensive flight dynamics assessment of a Twin-Fuselage aircraft at the conceptual design level, encompassing both static and dynamic stability, as well as preliminary flying qualities considerations.

2. Methodology

A 350-passenger long-range Twin-Fuselage aircraft with a Maximum Take-Off Weight (MTOW) of 160000 kg has been defined, consistent with the potential Top Level Requirements combination of interest for this configuration proposed in. A high-wing, joined-empennage layout was selected in accordance with the design considerations reported in.

The aircraft was modeled in OpenVSP, enabling the generation of a parametric aerodynamic model suitable for conceptual design studies. Static aerodynamic and stability derivatives, both longitudinal and lateral-directional, were obtained for a trimmed steady-flight condition representative of cruise regime. The selected aircraft weight corresponded to the midpoint of a mission defined at the midpoint of the MTOW-limited segment of the Payload–Range diagram, ensuring consistency with a representative high transportation capacity operating condition. Due to the limitations of panel methods in transonic regimes, the analysis was conducted at Mach 0.3 to ensure the robustness of the results in a linear aerodynamic framework.

Since OpenVSP does not provide unsteady aerodynamic derivatives, additional terms associated with the rate of change of the angle of attack were estimated using a well-stablished lag-in-downwash approach. In this formulation, the delayed response of the wake is modeled through a convection time between the wing and the horizontal tail, while the downwash gradient is obtained using the methodology of Etkin and Reid.

Following the model's static stability analysis, the longitudinal and lateral-directional dynamic modes were extracted. The five classical modes observed in conventional aircraft were obtained, and their modal characteristics were then evaluated against the flying qualities criteria defined in MIL-HDBK-1797-A, allowing a systematic assessment of the dynamic behavior of the Twin-Fuselage aircraft and its limitations in comparison to conventional aircraft.

The analysis indicated degraded lateral-directional behavior, including a divergent dutch roll mode leading to Level 3 flying qualities. To address this limitation, a Stability Augmentation System was designed and incorporated into the model to mitigate this behavior and achieve Level 1 flying qualities.

3. Results / Conclusions

The static stability analysis showed adequate stability for the Twin-Fuselage aircraft in the longitudinal and lateral motions. However, the destabilizing effect of the fuselages resulted in a slightly negative value of the stability derivative $C_{n\beta}$, indicating directional instability.

The modal analysis showed acceptable longitudinal behavior, with a Level 1 short period mode and a Level 2 phugoid mode. For the lateral-directional modes, the spiral and roll subsidence modes exhibited Level 1 flying qualities, partly due to the reduced fuselage separation selected to limit the increase in roll inertia relative to conventional aircraft. In contrast, the dutch roll mode showed unacceptable (Level 3) flying qualities. A classical yaw damper was found insufficient to mitigate this behavior. A dual-feedback Stability Augmentation System in sideslip angle and yaw rate was therefore implemented, highlighting the need for active control in Twin-Fuselage configurations.

Methodology for immersive AR/VR visualization of CFD simulations

Sergio Avila-Sanchez, Alvaro Cuerva-Tejero, Oscar Lopez-Garcia, Ricardo Fernandez-Aldama, Guillermo Torres-Pedrares
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1. Introduction / Objectives

Understanding complex flow structures, such as those from CFD simulations, may remain challenging in certain situations. Particularly when unsteady or three-dimensional effects are present. Immersive visualization with virtual or augmented reality (VR/AR) can improve spatial understanding of complex fields. However, the instantaneous application to flow postprocessing is limited, due to requirement disparity between quality CFD simulations and real-time rendering. CFD meshes typically present fine discretization, even non-uniform in space. This meshes are not suitable for efficient immersive visualization. To address this limitation, this work proposes a preliminary workflow to convert the dataset. The pipeline relies on open-source tools: ParaView for initial processing, Blender for geometric optimization, and BabylonJS for WebXR deployment.

2. Methodology

The output of high-fidelity CFD simulations is reconstructed into optimized datasets for immersive visualizations in three stages. The workflow relies on automatic extraction of isosurfaces as meshes, and scalar surface fields as material textures. Figures 1 and 2 illustrate the process, for a study of vortex-shedding computed with MapFlow. This study focuses on unsteady flow regimes associated with vortex shedding and lock-in phenomena. Here is presented a Q-criterion isosurface, to identify vortical structures, combined with a the vertical velocity.

First, the dataset is pre-processed in Paraview (Figure 1, left). Selected variables are exported in glTF format to preserve topology and associate material textures. This format acts as an intermediate layer between scientific visualization and the graphics engine. Second, the models are processed in Blender (Figure 1, right), to apply mesh simplification, topology cleaning, and controlled remeshing. The original datasets are associated to CFD-oriented mesh topology, resulting in excessively dense polygonal representations. The objective is to reduce polygon count while preserving the large-scale coherent flow structures relevant for aerodynamic interpretation. This asset optimization reduces storage and memory requirements, making web deployment feasible.

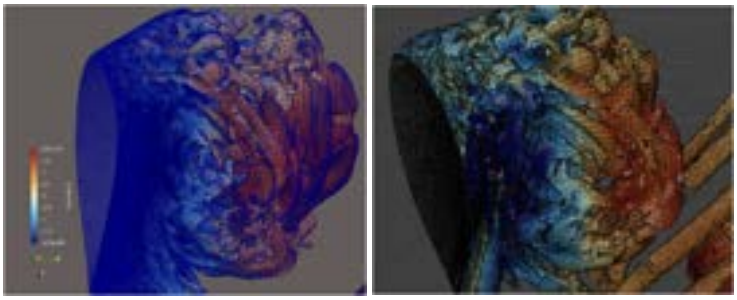


Figure 1. *Left, Q-Crit=1 isosurface in Paraview, with vertical velocity texture. Right, same with ~8% nodes in Blender.*

Finally (Figure 2), the optimized models are integrated in an immersive experience implemented in the game-engine BabylonJS, which enables cross-platform compatibility and easy deployment of VR/AR experiences to mobile devices and VR headsets. The experience supports immersive exploration of vortex structures and aerodynamic fields of some precomputed states (Q-Criterion, velocity, pressure fields,…). The result has been tested on consumer-grade hardware, i.e., Meta Quest 2 VR headsets and mobile devices. While currently limited to static snapshots of the flow field, the methodology can be escalated to include several time snapshots.

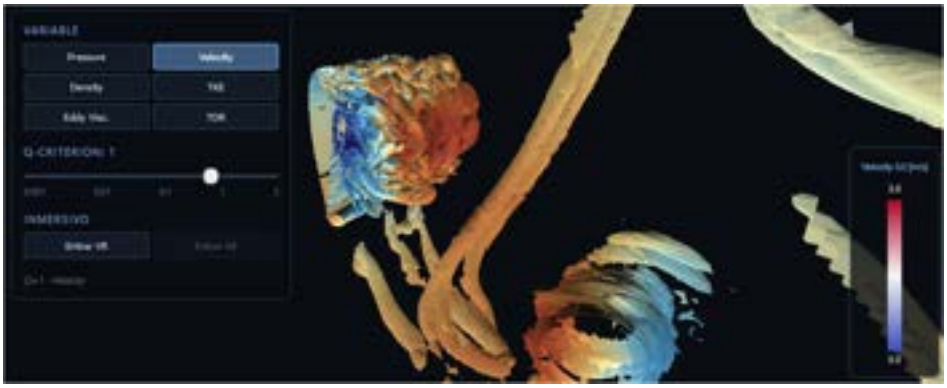


Figure 2. *Main page on the experience. Q-Crit=1 isosurface with vertical velocity material texture*

3. Results / Conclusions

The workflow explores a feasible, mostly unattended, conversion from high-fidelity CFD simulation into assets suitable for immersive visualization. The methodology addresses a critical limitation, the incompatible discretization between simulation-oriented meshes and real-time rendering for consumer-grade hardware. A substantial reduction in storage and memory requirements can be achieved, allowing deployment on lightweight platforms without requiring direct access to high-performance computers. The resulting assets preserve the spatial characteristics of the original flow structures. Immersive spatial inspection may facilitate qualitative interpretation of coherent flow structures, when superimposed with three-dimensional flow characteristics. Although the pilot implementation is restricted to static flow snapshots, it can be extended to time-dependent CFD datasets, interactive exploration strategies, or advanced scientific visualization.

Acknowledgment: This work has been supported by the Madrid Government (Comunidad de Madrid-Spain) under the Multiannual Agreement 2023-2026 with Universidad Politécnica de Madrid in the Line A, Emerging PhD researchers.

Aerodynamic Considerations for Autonomous Urban UAV Systems: Investigating Compact EDF Architectures for Close-Proximity Flight Operations

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1. Introduction / Objective

Future autonomous UAV systems are expected to support an increasing range of aerial services, including applications that contribute to sustainable transportation, infrastructure monitoring, and resource-efficient urban operations. While navigation, path planning, and collision avoidance have received considerable attention, vehicles operating in close proximity do not merely share airspace, they share an aerodynamic environment. During hover, altitude transitions, and conflict-resolution maneuvers, propulsion-induced wakes can influence neighboring vehicle stability in ways that position-based separation criteria do not capture.

As autonomous capabilities continue to advance, understanding these interactions becomes important for ensuring reliable operation in complex and dynamic environments. This work investigates whether propulsion architecture influences the aerodynamic conditions encountered during close-proximity flight. The central question is whether compact electrically ducted fan (EDF) architectures can support close-proximity autonomous operations while enabling highly integrated vehicle designs suitable for space-constrained urban environments.

2. Methodology

The investigation followed a systems-to-physics structure. Autonomous UAV operations were first examined from an operational perspective, including coordinated flight, collision avoidance, path planning, and U-space integration. A consistent observation emerged from this review: while vehicle positions are continuously monitored, aerodynamic interactions between neighboring vehicles are rarely treated as an explicit design consideration despite their potential influence on flight stability and operational robustness.

Compact EDF configurations were selected as a representative case study because tightly integrated propulsion layouts increase the likelihood of aerodynamic interaction effects while supporting reduced vehicle footprint, a desirable characteristic for sustainable urban UAV deployment. Experimental thrust measurements were conducted using both isolated and vertically stacked propulsion arrangements chosen to reflect the compact geometries often required by highly integrated aerial platforms. Rather than focusing on absolute propulsion performance, the experiments assessed the sensitivity of thrust generation to close geometric integration and aerodynamic interference. Measured thrust levels were subsequently compared across configurations to quantify interaction-induced performance deviations and identify potential aerodynamic coupling effects.

The operational relevance of the measured interaction effects was then investigated through nonlinear six-degree-of-freedom simulations implemented in MATLAB/Simulink. The simulation framework incorporated rigid-body translational and rotational dynamics, aerodynamic drag models, gravitational forces, thrust allocation algorithms, and PID-based stabilization loops representative of typical multirotor flight-control architectures. Multiple propulsion geometries were evaluated to determine how changes in propulsion placement influence overall vehicle dynamics.

Hover flight served as the primary assessment scenario because it combines continuous

control activity with operating conditions frequently encountered during close-proximity operations. Vehicle performance was assessed through inertial position tracking, velocity response, attitude stabilization, and pitch recovery behavior. Particular attention was given to identifying whether compact propulsion integration introduces dynamic penalties that could affect future autonomous operation in confined or aerodynamically complex environments.

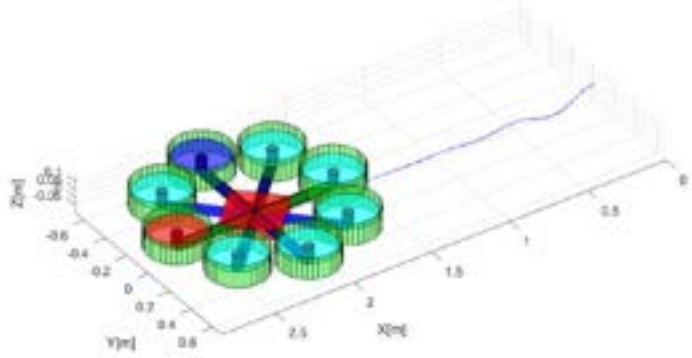


Figure 1. *Multicopter simulation model implemented in MATLAB/Simulink.*

3. Results / Conclusions

The experimental measurements revealed that closely integrated EDF configurations exhibited only minor thrust deviations, remaining below 5% across the investigated arrangements. Complementary flight-dynamics simulations further showed that stable hover can be maintained across propulsion geometries with substantially different levels of compactness, while differences in position tracking, velocity response, and pitch recovery remained limited.

Together, these findings suggest that compact EDF integration does not inherently introduce significant aerodynamic or flight-dynamic penalties within the investigated design space. This is particularly relevant because compact propulsion architectures offer a pathway toward reducing vehicle footprint while maintaining stable autonomous operation.

From a broader systems perspective, the results indicate that propulsion integration should not be viewed solely as a vehicle-level design problem. Instead, compact ducted propulsion may represent an enabling technology for future autonomous aerial systems operating in constrained environments where vehicle size, operational robustness, and close-proximity flight are critical considerations.

Enhanced Pilot Interfaces & Interactions for fighter Cockpit (EPIIC Project)

Chaired by:
Mr. Jean-Samuel De Visme (Thales Group, France)

Innovative Cockpit Display Technologies for Europe's Next-Generation Fighters

Christian Endl[1], Juan Carlos Gomez Pallarés[2]
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[2]Tecnobit SL

1. Introduction / Objectives

The perception of safety- and mission-critical information in the cockpit of modern fighter aircraft plays a central role in the work of fighter pilots. This is particularly true in view of the increasing responsibilities associated with future mission profiles. Pilots will have to work with a wide variety of different flight platforms, both manned and unmanned.
Furthermore, coordination and decision-making during missions are supported by the aircraft's systems to ensure that the right information is provided at the right time, without overwhelming the pilot with information. This can be achieved through new, innovative display technologies, as pilots must increasingly rely on instruments and displays to gain a comprehensive situational awareness that enables them to continue performing manoeuvres safely and precisely.

2. Methodology

In order to support the pilot in the cockpit of a future fighter aircraft, several new display concepts and technologies were investigated and evaluated. The focus is on three main concepts that show the most promise: seamless free-form display surfaces, autostereoscopic displays and multi-criticality displays.
The seamless free-form display replaces several small screens and control panels to improve space efficiency and situational awareness by integrating individually shaped, custom-cut LCDs directly into the forward instrument panel. The maturity, manufacturability and avionics suitability of LCD-based free-form displays, as well as the validation of cutting and sealing techniques that are compatible with aerospace standards are the most important aspects here.
Autostereoscopic displays enable 3D data to be displayed directly on the screen without the need for additional devices (e.g. glasses). Various 3D layers can be displayed, allowing information to be presented realistically and intuitively. Potential applications include mission planning, enhanced map display, camera views with depth information, and optimised warning displays. The focus is on the maturity and suitability of the technology for avionics, as well as the assessment of human performance when using a new 3D human-machine interface.
Multi-criticality displays enable information with different levels of reliability and safety to be shown on a single large display. This allows for the flexible allocation of display areas depending on the mission phase and the pilot's requirements, by combining flight-critical,

mission-critical and non-critical management information whilst maintaining the necessary levels of separation. The main advantage lies in the reduction of cockpit equipment, cabling, size, weight and power consumption, which are key factors for future adaptive cockpits and large-area display architectures in next-generation combat aircrafts.



Figure 1. *Concept of a possible future fighter display system*

3. Results / Conclusions

The results of the presented studies are twofold: on the one hand, several demonstrations were carried out for each technology, highlighting the displays' potential for future integration. These demonstrations also formed the basis for an initial assessment, taking human factors into account, in order to identify research gaps and technological challenges. On the other hand, a roadmap has been developed that addresses all the identified gaps and outlines the steps for the future development of such display technologies. Figure 1 shows a concept for one such possible future display system for fighter aircraft, in which all the different technologies are integrated into a single large central display.

Pilot Protection by Design for Future Helmet-Mounted Display Systems: Addressing Human Biomechanics from Early Design to Qualification

Sliman Ayad
THALES AVS France SAS

1. Introduction / Objectives

Modern Helmet-Mounted Display (HMD) systems have evolved into mission-critical interfaces providing pilots with enhanced situational awareness through the integration of navigation, sensor, communication and targeting functions. While these capabilities significantly improve operational effectiveness, they also increase the complexity of helmet architectures and may affect mass properties, centre-of-gravity location and overall ergonomics. As a

consequence, neck loading remains a major concern for military aircrew and may impact both mission performance and long-term health. Future HMD developments must therefore achieve an appropriate balance between operational capability and pilot protection. This paper presents the rationale behind a "Pilot Protection by Design" approach and discusses how physiological and biomechanical considerations can be integrated throughout the development lifecycle of future helmet systems. Particular attention is given to the contribution of the EPIIC project during the early design and concept definition phases.

2. Methodology

Pilot protection requires a comprehensive engineering approach extending from early concept definition to final system qualification. The starting point consists in identifying the factors contributing to cervical loading, including helmet mass, centre-of-gravity offset, aircraft acceleration environment, mission duration, pilot anthropometry and operational head movements. Understanding the interaction between these parameters provides the basis for defining relevant design criteria for future HMD architectures.

During system design, emphasis is placed on mass optimisation, centre-of-gravity management, equipment packaging and ergonomic integration. The objective is not only to reduce weight but also to ensure balanced architectures capable of supporting increasing operational functionalities without degrading pilot comfort or safety. Human factors are therefore considered alongside performance, operational and integration requirements during design trade-off activities.

Once candidate architectures have been defined, dedicated biomechanical assessments can be performed to evaluate pilot-equipment interactions and estimate head and neck loads under representative operational conditions. These evaluations support design maturation and provide objective criteria for comparing alternative solutions.

At later development stages, simulation activities, robustness evaluations and qualification testing may be conducted to verify system integrity and pilot protection under demanding operational conditions including impact, thermal exposure and ejection-related environments. These complementary activities provide continuity between design assumptions and system demonstration.

Within this overall framework, the EPIIC project contributes primarily at the upstream stages of development by integrating physiological, biomechanical and ergonomic constraints into future pilot interface concepts. As illustrated in Figure 1, EPIIC contributes to the understanding of future operational requirements and to the design of candidate HMD architectures while considering pilot safety from the earliest stages of concept definition. The objective is to ensure that pilot protection requirements become early engineering drivers rather than being addressed only during verification and qualification phases.

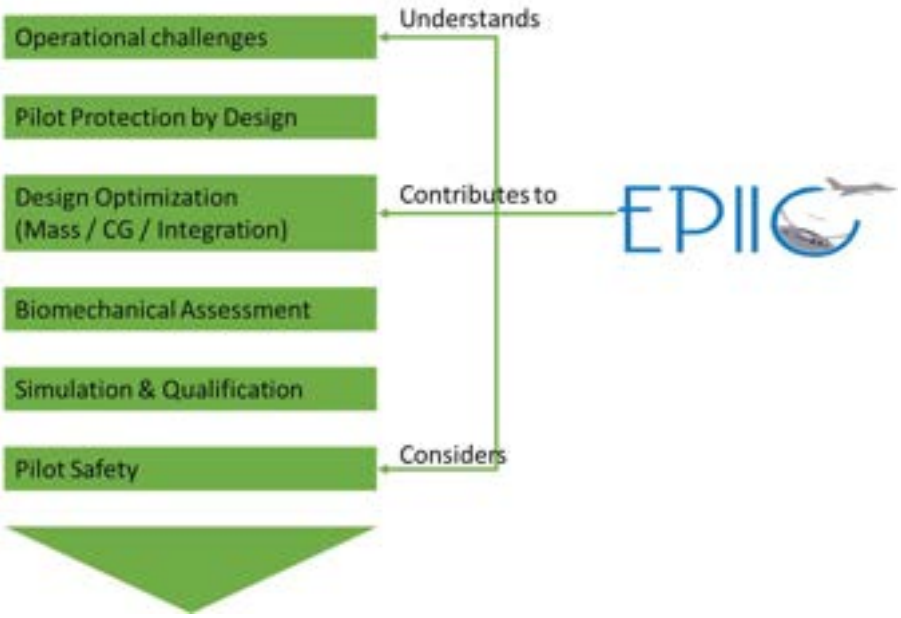


Figure 1. *Pilot Protection by Design framework for future HMD systems and contribution of the EPIIC project.*

3. Results / Conclusions

The presented approach demonstrates that pilot protection can be effectively integrated into the design process of advanced HMD systems. By combining ergonomic optimization, biomechanical evaluation, numerical simulation, and representative qualification testing, it becomes possible to balance operational performance with pilot safety requirements. Results highlight the importance of centre-of-gravity optimization and early human-factor integration in reducing cervical loading risks. The complementary use of simulation and physical testing provides robust evidence of system behaviour under realistic operational conditions. Within the EPIIC project, these methodologies contribute to the development of safer, more ergonomic, and operationally effective next-generation helmet systems, supporting both pilot performance and long-term health protection.

The User in Mind - A Human Factors focused MBSE Approach to Use Case Analysis

Engelbert Hartmann, Lucas Dullenkopf, Andreas Hemmert
Airbus, Germany

1. Introduction / Objectives

Despite the growing recognition of the relevance of human factors (HF) in the development of complex systems, their systematic integration into the working level model-based system engineering (MBSE) processes remains inconsistent and often ad hoc. This mismatch leads to expensive late-stage redesigns of systems that meet technical specifications yet fail to support effective human operation. Especially in the context of military jet operation, the focus of the EPIIC project, identifying human needs, strength and limitations early in the

process is paramount for usability and mission success. Therefore, the presentation proposes a method to integrate human centered design (HCD) principles into existing industry MBSE workflows, enabling the application of human factors methods in MBSE-driven human machine interfaces (HMI).

2. Methodology

The methodology presented originates in the need to provide guidance for technology developers in order to focus their efforts on future operational and user needs. Thereby, steering the development of innovative and disruptive technologies for future fighter cockpits on the basis of far-sighted use cases. To ensure that technical developments are usable and integratable into an overarching concept of a future cockpit, early adoption of HCD, beginning in the initial stages of use case analysis, was implemented into the MBSE toolchain. This approach also addressed the necessity for traceability, as assumptions regarding capabilities frequently evolve. The following steps will be presented:

- Description of the Operational Context: The operational context is described using a proven framework for the creation of military scenarios. It defines relevant actors, the threat landscape, and geopolitical conditions, thereby outlining the key operational and environmental assumptions and the general setting of the conflict. This high-level description informs the mission vignette, which distills the broader scenario into a discrete, self-contained narrative, capturing a specific decision point within a defined temporal and spatial segment of the broader context.
- Use Case Definition: Embedded into the higher-level setting, the defining elements of the UC are outlined, such as preconditions, involved actors, triggers, the main flow of events, and postconditions.
- Use Case Analysis: The nominal flow of the use case is decomposed into discrete tasks through HFE methods, such as Hierarchical Task Analysis (HTA). In the first step these tasks are logically sequenced, independent of operator or system allocation and modeled with SysML. This is used to foster the communication between Human Factors Engineering and System Architecture. The approach has been aligned to existing systems engineering methods and fills missing gaps. In a subsequent step building upon the insight, developed through modeling the results of the HFE analysis, default automation levels are defined using the General Automation Level Allocation (GALA) framework, an automation framework purpose built by Airbus Defence and Space GmbH. • Output Derivation: The model generated in previous steps is used to derive key outputs, including HMI requirements, operator information needs, and interaction modalities. These outputs are integrated into the broader MBSE workflow to ensure alignment with HMI design and operational requirements.

3. Results / Conclusions

The presentation demonstrates a viable method for integrating HF analysis into MBSE-driven HMI design, enabling early validation of pilot needs and facilitating the definition of disruptive cockpit technologies based on real-world operational requirements.

Next-Generation Multi-Modal Interaction Systems in Advanced Fighter Cockpits

Sergio Sacristán, José Alfonso García Rodríguez
Airbus, Spain

1. Introduction / Objectives

In the contemporary theatre of high-intensity, multi-domain operations (MDO), the volume of sensor-fused data presented to a pilot has reached a critical inflection point. As we transition toward 6th generation air superiority platforms, the traditional Pilot-Vehicle Interface (PVI) is no longer merely a conduit for control but has become the primary bottleneck in mission effectiveness. Traditional manual interfaces rely on discrete motor responses that impose a significant Workload (WL) overhead.

To maintain a competitive edge, the cockpit must evolve from a reactive toolset into an intuitive, symbiotic partner. This evolution requires a fundamental shift from mechanical input to multi-modal interaction (MMI) systems by enhancing the Human Machine Interface (HMI) that leverage the pilot's natural physiological and neurological channels. In this EPIIC European project, new technologies are pushed to a higher level of intuitive interaction to achieve such objective via innovative interaction modalities with the pilot.

2. Methodology

The shift towards a more integrated and intuitive partner is worked out thanks to new display technologies and via additional communication channels between the pilot and the vehicle. These additional channels are possible thanks to new technical developments in the sensors domain and this project has identified a series of them to be considered: Gesture-Based Interaction Systems (GBI), Advanced Eye-Tracking and Ocular Targeting, Brain-Computer Interface (BCI) and Neural Command, Natural Language Processing (NLP) and Voice Synthesis (VS).

However, many inputs and output channels could lead to clashed and confusion and here is where the Multimodal Integration process comes to provide the solution. The Multimodal Integration is the process of testing these selected techonologies altogether with the target to assess which is the optimum combination in the various situations, as some technologies may provide the same functionality concurrently and that may lead to undesirable situations

The process starts by the selection of those technologies with proven results in terms of data acquisition and data interpretation and integrates them into a simulator that tests all of them together. The design and assessment phase needs several steps of testing to identify what combination of interactions are more adequate to provide a reliable and solid input, which also requires to consider the operational environment of the end users and the type of command that could be attributed to a particular technology and this may also class some of them for critical commands and others for non-critical commands; it is unlikely that a

missile could be launched with simple "thumbs-up", while a combination of some of these novel inputs could be considered acceptable. Additionally, the perception of these new technologies when coming from the "legacy world" leads to some biases in the test results and leads to require several runs until a stable assessment is achieved.



3. Results / Conclusions

Currently in Europe this multi-modal integration has not yet progressed into an operational solution and it is in early stages, even if progressing a good speed and providing a solid baseline of options for different missions and solutions. There is still work to be done to move from a laboratory environment into a realistic environment and even to flight testing, as technologies are still not solid enough for such breakthrough. EPIIC2 is the continuation of EPIIC where this leap will be dared to get closer to a real cockpit with a real pilot situation and a more solid optimum mix of input technologies.

Ultimately, the paradigm shifts from 'Pilot as Operator' to 'Pilot as Mission Commander' in 6th generation aviation, which will no longer just operate a machine, but be a direct an extension of their own intent, leaving tactical piloting roles to algorithms while focusing entirely on mission targets, command and control.

Maintenance, Repair & Overhaul (MRO)

Chaired by:
Dr. John-Alan Pascoe (TU Delft, Netherlands)

Embedded FBG-Based Smart Composite Panels for Aerospace Structural Health Monitoring and Impact Detection

Alessandro Aimasso, Paolo Maggiore, Matteo D.L. Dalla Vedova
Politecnico di Torino, Italy

1. Introduction

The increasing use of carbon fiber reinforced polymer (CFRP) structures in aerospace applications has introduced the necessity for lightweight, distributed, and highly reliable sensing systems capable of operating under harsh environmental and operational conditions . In this context, Fiber Bragg Grating (FBG) optical sensors represent a promising solution due to their immunity to electromagnetic interference, minimal invasiveness, multiplexing capability, and sensitivity to multiple physical parameters such as temperature, strain, and vibration . The direct integration of optical sensors within structural components enables the development of smart composite structures capable of autonomously providing real-time information regarding their operational and structural state . This work presents the development, manufacturing, and experimental validation of smart CFRP panels with embedded FBG sensors specifically conceived for aerospace Structural Health Monitoring (SHM) applications. The proposed approach focuses not only on the integration of optical sensing within the laminate, but also on the development of a robust and scalable architecture suitable for practical implementation in lightweight aerospace structures.

2. Methodology

The first phase of the activity concerned the realization of composite specimens manufactured through manual layup and vacuum bagging techniques using quasi-isotropic CFRP laminates. FBG sensors were embedded directly between laminate plies during the manufacturing process, while dedicated routing strategies were developed to minimize stress concentrations and preserve fiber integrity. Preliminary thermal characterization activities demonstrated excellent linearity, repeatability, and sensitivity of the embedded sensors, validating the feasibility of direct optical sensing integration within composite structures. The obtained results also enabled the estimation of internal thermal gradients and heat flux through the laminate using exclusively optical measurements. Following the preliminary validation phase, the work evolved toward the realization of fully integrated smart composite panels featuring improved optical routing and connector-based integration strategies. Particular attention was devoted to one of the main critical aspects of embedded optical sensing systems, namely the fiber exit region and connector robustness. Experimental activities highlighted the risk associated with resin infiltration and stress concentration phenomena during curing and handling operations. To overcome these limitations, a protected connectorized architecture was developed through the physical isolation of the optical interface during lamination and the implementation of a dedicated protective housing. The resulting configuration significantly improved mechanical robustness, maintainability, and scalability toward more complex distributed sensing networks. The proposed architecture was subsequently validated through static and dynamic experimental campaigns.

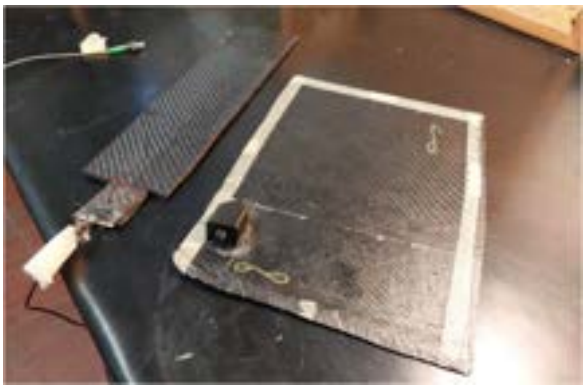


Figure 1. *CFRP specimens tested.*

3. Results / Conclusions

Static loading tests demonstrated excellent repeatability, negligible hysteresis effects, and high sensitivity to localized load applications. Furthermore, the use of dual embedded FBG sensors positioned along different directions enabled the extraction of spatial information related to load distribution across the composite panel. Dynamic impact tests were performed through controlled low-energy impacts generated by a calibrated falling mass. The experimental results demonstrated the capability of the embedded optical sensing architecture to clearly detect impact-induced transient responses and oscillatory phenomena with satisfactory signal-to-noise ratio, even under small deformation conditions. The obtained results confirm the feasibility of using embedded FBG networks for lightweight real-time SHM applications involving impact detection and potentially localization functionalities. The proposed solution therefore represents a promising step toward the realization of multifunctional aerospace composite structures integrating both load-bearing and sensing capabilities within the same component. Future developments will focus on the extension of the sensing network, advanced impact localization methodologies, environmental testing activities, and the integration of data-driven diagnostic and prognostic algorithms for next-generation intelligent aerospace systems.

Opportunities and challenges of resonant ice protection systems for regional aviation

Valerie Pommier-Budinger[1], Marc Budinger[2], Pierre Bonhomme[3], Yohan Sabathe[1], Jason Pothin[1], Valerian Palanque[3]
[1] ISAE-SUPAERO, France
[2] Institut Clément Ader, France
[3] Airbus, France

1.Introduction / Objectives

Climate change and the need to decarbonize the aviation industry are exacerbating the demand for new ice protection systems. Climate change may indeed generate a greater number of critical meteorological events, including temperature inversions and freezing rain, and new aircraft concepts present new challenges:

- Improved aerodynamic performance and lighter structures: wings with higher aspect ratios increase the surfaces to be protected, composite structures are incompatible with certain thermal de-icing technologies.

- Electrification of energy sources: new electrothermal or electromechanical technologies are required.

- Reduction in condensation trails: lower flight altitudes mean longer periods in icing zones.

The current anti-icing systems are unable to meet these new requirements. Resonant electromechanical IPSs are currently investigated to alleviate the limitations of existing systems . The study aims to assess the potential of this technology for regional aviation.

2.Methodology

Resonant electromechanical IPSs deform the airfoil skin to detach the ice with high strain rate, allowing for de-icing with negligible surface deformation, preserving aerodynamic performance. They use actuators to excite the wing's skin at frequencies that correspond to the structure's resonant frequencies. Thanks to the mechanical resonance of the structure, the vibrations are amplified without requiring too much power, and once the mechanical properties of the ice are exceeded, the ice sheds (Figure 1).
This study will address four points to push the limits of this technology.

(i) A new concept of resonant de-icing system based on the combination of flexural and extensional modes will be proposed to increase the efficiency and power requirements. This concept will be analyzed thanks to a multiphysics Finite Element Analysis and a coupled criterion for ice fracture analysis based on stress and energy release rate, for a module representative of a leading-edge section of regional aircraft.

(ii) The latest advances in actuator design will be presented. Notably, the analysis will focus on a design for a pre-stressed piezoelectric actuator that allows for a large bandwidth and is robust, impact-resistant and easy to maintain.

(iii) The requirements for tracking the resonance modes will be analysed, and a schema for closed-loop control of resonant IPSs will be proposed to minimise de-icing time and maximise the performance of such systems. The control architecture must address the issue of the rapid variation in the resonance to be tracked due to variations in the mechanical parameters when ice fractures. The architecture is based on d-q vector control. Compared to the open-loop strategy currently used to control resonant ice protection systems, this architecture will enable faster de-icing.

(iv) The opportunities of a resonant IPS for regional aircraft will be assessed by providing mass and power balance of this system at aircraft level. This analysis will use pre-stressed piezoelectric actuators. The power supply and electrical cables will be considered to provide a holistic view of the technology's potential.

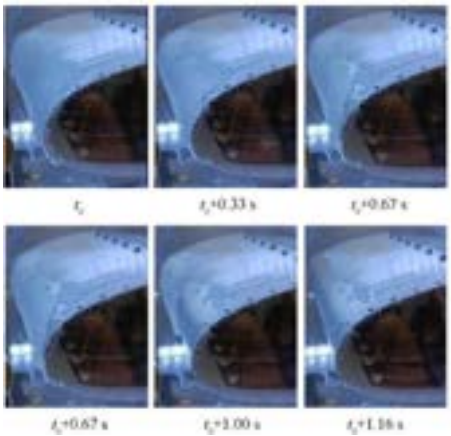


Figure 1. *De-icing test on a leading edge with resonant IPS.*

3. Results / Conclusions

The study will review the current challenges faced by IPSs regarding the choice of resonance modes, actuation systems, and mode tracking. It will propose solutions to enhance the performance of this technology and draw conclusions about the potential of resonant ice protection systems for regional aviation.

Noise Reduction of Laser-Ultrasonic Signals in CFRP Using a Hybrid Deep Learning Approach

Aditi Mhatre, Caspar Wasle, Rebecca Rodeck, Gerko Wende
DLR – German Aerospace Center

1. Introduction / Objectives

Ultrasonic inspections are one of the techniques employed in non-destructive testing to ensure the safety of an aircraft. It is an acoustic inspection method that excites ultrasound waves with a laser to identify potential defects within materials . The examination of ultrasonic signals enables the localization and characterization of defects, making it valuable for their early detection. However, the presence of noise is inevitable during the inspection process, leading to signal distortion, which makes data interpretation more challenging. This is a core weakness of laser ultrasound, as due to the principle of contactless excitation and measurement, the received signal energy is very low . Deep learning methods have been increasingly adopted for industrial applications and offer a robust solution to noise reduction. This paper aims to develop a hybrid deep-learning approach combining U-Net with Fast Fourier Transform (FFT) to denoise ultrasonic signals for inspections of carbon fiber reinforced polymers (CFRP).

2. Methodology

We implement a hybrid deep-learning framework to denoise signals collected via a laser ultrasonic setup for defect examination in carbon fiber-reinforced polymer (CFRP) plates. Noisy data was acquired experimentally using a laser-ultrasonic system equipped with an optical microphone. The preliminary dataset is comprised of 200 samples, each containing a noisy measurement and its corresponding clean ground truth. Clean signals were derived by averaging multiple acquisitions at the same location to suppress random noise and approximate the deterministic wave response. These measurements were collected from CFRP test specimens. The hybrid architecture employed an enhanced U-Net model with a Fast Fourier Transform (FFT). The first layer implemented FFT to explicitly capture spectral components from the ultrasonic signals. These features were concatenated and passed to the standard U-Net encoder-decoder architecture with three downsampling/upsampling levels (16-32-64 feature channels) and a bottleneck (128 feature channels) to preserve multi-scale signal details. The network was preliminarily trained for 50 epochs using the Adam optimizer with a Mean Squared Error (MSE) as the loss function. The dataset split maintained a 70:30 training-validation ratio. During training, synthetic Gaussian noise was applied to clean signals to augment the dataset and improve generalization. The sliding window approach utilized 256-sample windows to perform localized frequency-aware noise suppression. Model evaluation focused on signal-to-noise ratio (SNR) and mean squared error (MSE), providing quantitative assessment of noise reduction in ultrasonic signals.

3. Results / Conclusions

The proposed hybrid FFT-U-Net demonstrated quantitative denoising performance, achieving preliminary results of +5.3 dB average SNR improvement across the test dataset. The model maintains consistent performance across frequencies, particularly in high frequencies, where classical filters exhibit significant signal distortion. These findings suggest that the hybrid architecture could minimize noise to enhance defect detectability in laser-ultrasonic CFRP inspections, and supporting reliable NDT workflows. Future work will extend the model to denoise signals across different materials and validate its performance on in-service aircraft components.

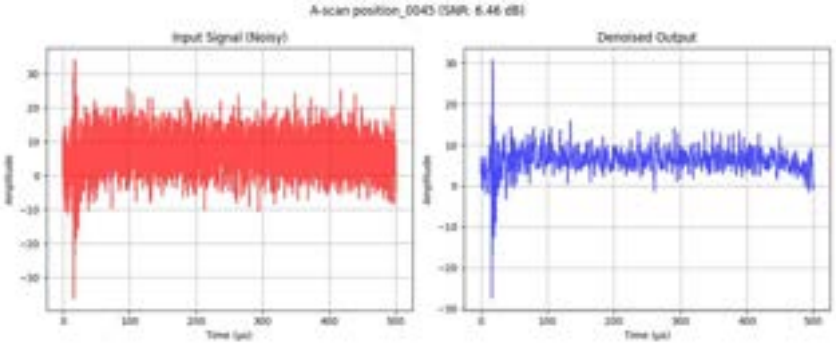


Figure 1. *Preliminary results of the proposed method when tested on CFRP data. The figure depicts the input signal for the model (left), and the resulting denoised output (right), which improves the SNR by 6.46 dB.*

AJP-Based Strain Sensing for CFRP Structures: From Anisogrid Validation to Tank-Level Application

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1. Introduction / Objectives

This work presents a progressive validation and application strategy of Aerosol Jet Printing (AJP) strain sensors for CFRP aerospace structures. AJP sensors were first integrated into anisogrid panels characterized by complex geometries and anisotropic stiffness distributions, where their response under cyclic compressive loading was assessed against conventional strain gauges to verify strain measurement consistency and support a local-to-global strain transfer approach. Based on this validation, the sensing strategy was extended to full-scale CFRP tank structures manufactured using an innovative water-soluble expandable mandrel technology, enabling integral geometries with internal reinforcements. Both anisogrid panels and one-piece tanks are representative of advanced lightweight aerospace components. The objective is to demonstrate the applicability of AJP sensing from controlled test articles to real structures, combining numerical simulations, sensor optimization, manufacturing, and experimental testing.

2. Methodology

CFRP anisogrid test articles ("double-clepsydra" configuration, approx. 207.5 × 173.5 × 24.8 mm) were manufactured by robotic winding of dry carbon tows, followed by vacuum-bag liquid epoxy resin infusion and autoclave curing. AJP copper-based strain sensors were deposited on the rib surfaces using an OPTOMEC AJ5X system, with their sensitivity axis aligned with the local rib axis. The Gauge Factor (GF) was optimized through a coupled ABAQUS®/COMSOL Multiphysics® workflow, correlating electro-mechanical response with the local strain field derived from FEM simulations. Sensor readings were validated against conventional strain gauges under cyclic compressive loading, confirming the local-to-global strain transfer approach on complex lattice geometries. Building on this validation, the sensing strategy was extended to full-scale CFRP tank structures while structural design of the tank was performed using Ansys LS-DYNA® (LS-PrePost-4.10.4-x64, MPP V14.4® solver).

Since the resulting integral geometry prevents mandrel extraction, an Addyx "Carbon Exoskeleton" expandable water-soluble type was adopted. Pre-impregnated sheets were manually positioned on the mandrel, ensuring alignment and absence of defects. For the reinforcing configuration slots were machined into the mandrel to house CFRP prepreg ribs, forming the internal stiffening frame and enabling full skin-rib alignment without geometric distortion. Two tank variants were produced: unreinforced (skin only) and rib-reinforced, to enable direct structural comparison. AJP sensors were applied on both configurations with sensitivity axes parallel to the compressive load direction. In the rib-reinforced tank, the uniaxial stress state in the ribs enables direct back-calculation of the global compressive load; sensors on the skin operate under a biaxial stress state, requiring the extended strain transfer formulation derived from the FEM model. Experimental tests were carried out under quasi-static compressive loading, acquiring load, displacement, and strain data simultaneously from AJP sensors and reference strain gauges, allowing direct numerical-experimental correlation.

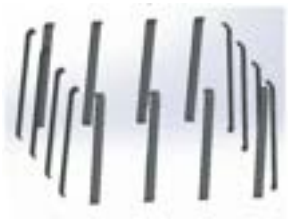


Figure 1: *The reinforcing structure of the ribs*

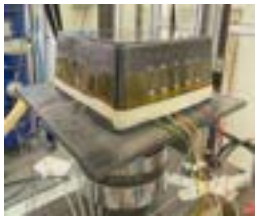


Figure 2: *Final sample in the testing phase*

3. Results / Conclusions

AJP strain sensors showed consistent agreement with conventional strain gauges on anisogrid CFRP panels under cyclic compressive loading, supporting the adopted strain transfer approach for complex lattice structures. Building on this validation, the sensing methodology was successfully applied to CFRP tanks manufactured with a water-soluble mandrel, demonstrating reliable strain measurement in full-scale components with integral geometry. Experimental tests highlighted the improved load-bearing performance and reduced deformation of the rib-reinforced configuration compared to the unreinforced one, confirming the effectiveness of the structural design. The combined use of FEM simulations (ANSYS LS-DYNA), multiphysics optimization (COMSOL®), real manufacturing processes, and experimental validation provides a consistent framework for integrating AJP sensing into advanced aerospace structures, enabling effective monitoring of complex CFRP components.

Automated Digitization of Maintenance Handwritten Data Using Multiple Fine-Tuned Models

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[2] KLM Engine Services, Netherlands

1. Introduction / Objectives

At an international engine maintenance service, engine re-assembly depends on precise measurements across fan, compressor, and turbine modules, as deviations can affect performance. Although predictive maintenance is increasingly used in aviation to reduce

failures and operational downtime, the maintenance plant adoption is limited by how assembly data is captured. Measurements are recorded on paper-based sheets containing mixed printed and handwritten entries, later scanned into PDFs, creating accessibility challenges and restricting structured analysis . Earlier work by Mairuf et al. demonstrated the feasibility of semi-automated handwritten data extraction using OCR, but accuracy limitations and narrow file-format coverage prevent operational deployment. Therefore, the objective of this work is to enhance and extend that semi-automated extraction methodology to reliably extract, validate, and structure performance-critical assembly data, improving recognition accuracy and enabling its integration into predictive maintenance workflows.

2. Methodology

The developed architecture integrates multiple machine learning models into a pipeline which automatically extracts data from the maintenance files into structured outputs. This pipeline can be divided into three consecutive stages: Detection, recognition, and extraction. To validate model outputs throughout this process, a HITL document is generated by flagging low-confidence predictions. The detection stage begins with the pre-processing of each PDF by converting it into a normalized and enhanced image. These images are used as input for a trained YOLO model, which identifies regions containing either printed or handwritten text. The YOLO model outputs classified bounding boxes of detected regions. Within the recognition stage the detected regions are cropped and fed into the OCR models. PaddleOCR is applied on the printed text regions, while TrOCR is used for handwritten text regions. The generated transcriptions are then combined with their corresponding bounding boxes, providing a representation of both text contents and spatial layout. The outputs from the recognition stage are then intended to be fed into a trained GeoLayoutLM model within the extraction stage. Within the proposed approach, the text content, spatial layout, and visual features would be processed to predict the semantic meanings and relations within the document. Although the training and implementation were outside of the scope of this paper, the architecture was selected as a suitable method for structured data extraction. In addition to the extracted document information, file names contain information which is extracted to construct a header of each document, which could be used to perform search-specific queries. To ensure reliable outputs, the system utilizes a HITL mechanism that flags low confidence model predictions throughout the three processing stages. The flagged reports were saved to a comma-separated values (CSV) file, which includes information about the processing stage, location of error within the file, context of the report, and confidence values, which highlight the need for manual verification. A HITL checkbox is also included in the final structured output to remind users if values require further validation.

3. Results / Conclusions

The developed detection and recognition pipeline demonstrated strong performance, with YOLO achieving mAP50 of 0.924 and mAP50-95 of 0.755 on the validation set, results that were confirmed on unseen test data. Handwritten text, the most critical information in the documents, showed the highest detection accuracy, while printed text was also reliably identified. Recognition performance was similarly strong: printed text remained consistently accurate, and handwritten transcription using the fine-tuned TrOCR model achieved an average CER of 0.0108, WER of 0.0518, and F1-score of 0.9627, validating earlier findings from

Mairuf et al. (2025). Although the extraction stage was not fully implemented, structured visual outputs demonstrated the feasibility of automated data integration. Reliability evaluation showed that confidence-based filtering successfully flagged over 70% of incorrect predictions. Overall, the results confirm that combining YOLO, PaddleOCR, and TrOCR provides a reliable foundation for automatically extracting and structuring assembly-sheet data, enabling future predictive-maintenance applications.

Testing & Simulation based analysis of aircraft structures

Chaired by:
Mr. Dieter Kohlgrüber (German Aerospace Center (DLR), Germany)

A Computational Framework for Predicting the Mechanical Properties of Recycled CFRP Laminates

Ilektra Tourkantoni, Konstantinos Tserpes
University of Patras, Greece

1. Introduction / Objectives

This work presents a computational multi-scale framework for predicting the mechanical performance of unidirectional (UD) carbon fibre reinforced polymers (CFRPs) manufactured from recycled carbon fibres. The framework integrates micromechanical modelling, numerical homogenization, and coupon-scale finite element (FE) analysis to establish predictive links between fibre-level properties and laminate mechanical response.

2. Methodology

As an application case, the framework is employed to evaluate carbon fibres recovered via plasma-assisted solvolysis. Following recycling, single-fibre tensile tests and microbond tests were conducted to characterize the mechanical properties of TR30S carbon fibres and their interfacial behavior. These experimentally derived parameters, complemented by literature data, were used as input to micromechanical models and representative volume elements (RVEs) in order to compute the elastic properties and strengths of UD plies.
The FE models were developed using the LS-DYNA software. At the coupon scale, numerical simulations were performed under axial tension, axial compression, and three-point bending loading conditions, enabling the prediction of key laminate properties, including longitudinal stiffness, longitudinal tensile strength, longitudinal compressive strength, and interlaminar shear strength. Model predictions were validated against experimental measurements, showing overall good agreement.

3. Results / Conclusions

Overall, the study demonstrates that the proposed computational framework can serve as a versatile tool for assessing the mechanical performance of recycled CFRPs across different recycling routes, thereby supporting accelerated material qualification and the design of sustainable composite structures.

Simulation of aircraft kinematics during ditching using a meshfree pointset method

D. Kohlgrüber, M. Petsch
DLR – German Aerospace Center

1. Introduction / Objectives

A safe ditching behavior of new aircraft has to be demonstrated during the aircraft certification process . In the past this certification was mainly achieved by representative scaled model tests or by similarity considerations with already certified design variants in case of minor changes in aircraft shape or size.
In parallel to the options mentioned above, numerical simulations using different fidelity levels are increasingly used to support ditching investigations, mainly to assess hydrodynamic loads for subsequent strength analyses . Recent analysis using numerical Hi-Fi methods raised the question, in how far scaled model tests are representative for full size aircraft ditching, as some hydrodynamic effects such as cavitation are not present in scaled tests, but are considered to have a significant influence on the aircraft kinematics.
In this paper a CFD based meshfree numerical method will be used to investigate specific effects such as shape of fuselage, position of tailplane and sea state on the ditching behavior of real size aircraft models.

2. Methodology

In the presented work a fully coupled CFD / CSM approach is used to model aircraft ditching. In this approach the flow field is calculated using the so-called Finite Pointset Method, initially developed by Kuhnert et.al. as implemented in the commercial Finite Element Package VPS . In this approach a flow solver with implicit time integration and a structural solver with explicit time integration are coupled and solved simultaneously as presented in for initial studies on aircraft ditching.
One result, presented in shows that the similitude of Froude's law may lead to non-realistic low pressure below the aircraft fuselage for realistic transport aircraft size and therefore cavitation is likely to occur in a real ditching, which limits the pressure to the vapor pressure of the water. Using an artificial pressure limit a full-scale generic aircraft shape according to NACA-2929 tests showed skipping instead of a smooth landing.
In this paper, further simulation studies will be presented. In the first part the ditching kinematics of a generic transport aircraft will be analyzed in detail. Special focus will be given to the influence of the horizontal tailplane which limits the pitching up for a classical configuration. Although calm water conditions may be considered for ditching certifications the influence of sea state on the aircraft behavior will be discussed in the second part of the paper. To support the almost automatic analysis of different ditching conditions a process including wave generation (regular and irregular wave spectra), positioning of the aircraft and launching the ditching analysis has been developed. This process allows landing parallel to the waves or in any other direction with respect to the waves.

3. Results / Conclusions

In Figure 1 selected results of the current ditching simulation process are summarized. The plots on the left side show the stabilizing influence of the HTP on the aircraft kinematics. While

the upper plot shows the full aircraft 800 ms after the first water contact the second plot shows the same simulation when the HTP is omitted from the wall definition for the flow solver (simple assumption for a T-tail configuration). In this comparison the HTP limits the pitching up of the aircraft which leads to an earlier contact of the engines and a more stable ditching kinematics. On the right side the same generic transport aircraft is shown during a ditching parallel to a system of regular waves with a wave height of 1.5 m and a wavelength of 32 m. In the established process the initial flow conditions of the water are calculated using a wave maker over a period of up to 50 s and the aircraft is then launched in a restart with arbitrary initial conditions incl. position, velocity and pitch angle to save computation costs.

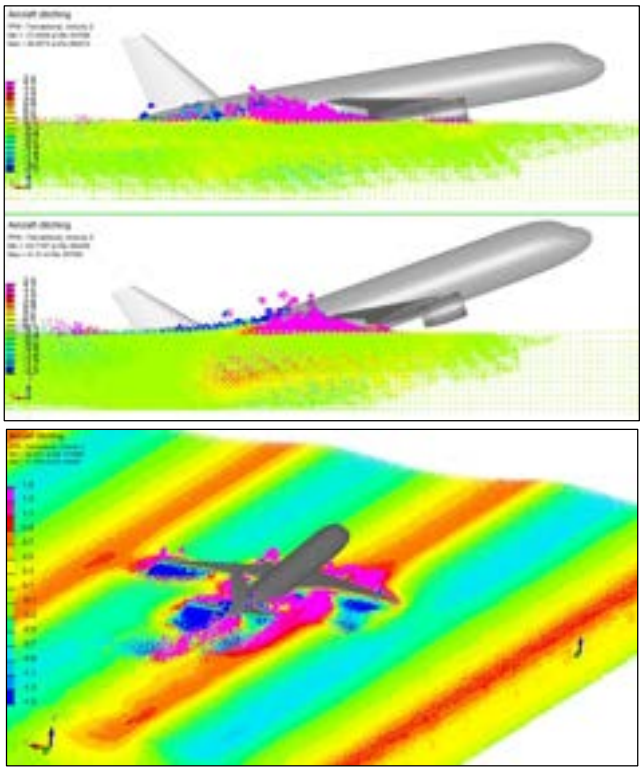


Figure 1. *Influence of HTP on ditching kinematics (left) and water domain with regular wave pattern at ditching simulation (right)*

Aero-Structural Modelling of a Two-Degree-of-Freedom Movable Wingtip for Aeroelastic Response Analysis

Peide Zhou, Bocheng Zhang, Chao Yang
Beihang University, China

1. Introduction

Smart morphing structures are increasingly used in advanced aircraft design because they can adapt aerodynamic and structural configurations to different flight conditions and mission requirements. As a potential aeroelastic tailoring device, the movable wingtip has

attracted attention for gust load alleviation, flutter suppression and flight-envelope expansion . However, studies on multi-degree-of-freedom and multifunctional smart wingtips remain limited. High-aspect-ratio wings can improve aerodynamic efficiency, but their structural flexibility may induce significant aeroelastic phenomena, including large deformation, modal coupling and flutter . Therefore, this work develops a preliminary aero-structural modelling framework for a high-aspect-ratio wing equipped with a two-degree-of-freedom movable wingtip. The wingtip is treated as a rigid body connected to the main wing through two independent rotational degrees of freedom, corresponding to roll and pitch deflections. The objective is to establish a unified procedure linking nonlinear structural dynamics, unsteady aerodynamic modelling and aeroelastic model reduction.

2. Methodology

The main wing is represented by a finite-element beam model with six degrees of freedom at each structural node. Bending–torsion coupling and moderate geometric nonlinearity are considered in the structural formulation. The movable wingtip is modelled as a rigid body, and its two rotational degrees of freedom are incorporated into the global set of generalized coordinates. Based on the kinetic and potential energy expressions of the coupled main-wing–wingtip system, the nonlinear equations of motion are derived. Particular attention is paid to the inertial coupling between the translational and rotational degrees of freedom of the main-wing tip and the two deflection degrees of freedom of the movable wingtip.

The structural system is first analyzed under different fixed wingtip deflection configurations without aerodynamic coupling. Modal analysis is performed to investigate the influence of wingtip deflection on the natural frequencies and mode shapes. Static response curves are obtained by gradually applying external loads, so as to evaluate the variation of wingtip displacement and torsional response with load level. Time-domain dynamic responses are further computed using the Newmark-β method under prescribed force and moment excitations.

For aerodynamic modelling, an unsteady aerodynamic model is established for different fixed wingtip configurations using the doublet-lattice method . A structural–aerodynamic interpolation procedure is introduced to project finite-element structural motion onto the aerodynamic grid, allowing the generalized aerodynamic force matrices to be obtained over a range of reduced frequencies. Roger's rational function approximation is then applied to fit the frequency-domain unsteady aerodynamic forces and transform them into a time-domain state-space representation. This procedure provides the basis for subsequent flutter analysis and control-oriented aeroelastic modelling. The overall aero-structural modelling and analysis workflow is summarized in Fig. 1, including structural modelling, structural response analysis, DLM-based unsteady aerodynamic modelling, generalized aerodynamic force calculation, Roger approximation and subsequent aeroelastic applications.

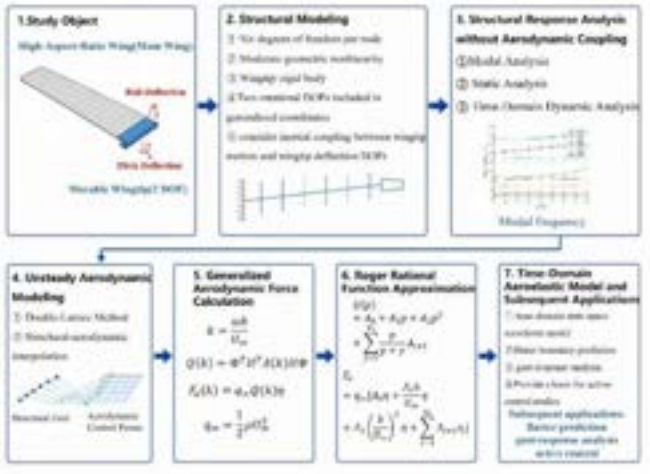


Figure 1. *Overall aero-structural modelling and analysis workflow for the two-degree-of-freedom movable wingtip.*

3. Conclusions

Preliminary structural analyses show that the influence of wingtip deflection on the modal frequencies of the coupled main-wing–wingtip system is mode-dependent. The investigated frequencies vary continuously with deflection angle; the lowest modes are only slightly affected, while some higher modes show greater sensitivity. Static analyses indicate that, under gradually increasing wingtip concentrated force, the vertical displacement magnitude increases monotonically with a nonlinear trend. Under gradually increasing wingtip torque, the torsional angle remains approximately linear with the applied torque. Time-domain simulations show that, under selected sinusoidal excitations, the wingtip displacement and torsional responses undergo a short transient stage and then exhibit bounded periodic behavior, with a clear low-frequency dominant peak in the spectrum. These results characterize structural responses under representative loading conditions rather than flutter stability. In addition, DLM-based aerodynamic modelling and Roger approximation have been established for subsequent aeroelastic state-space modelling.

Progressive Damage Analysis of Stiffness-Transition Regions in Composite Aerostructures Under Static and Impact Loading

Hande Girard, Yusuf Ozan Çakır, Dilan Ezgi Yücel

1. Introduction / Objectives

In composite aircraft wing structures, ply drop-off regions are introduced to achieve thickness tailoring, reduce structural weight, and establish required stiffness distributions that influence aeroelastic deformation and the preservation of aerodynamic shape for operational requirements. However, ply drop-off configurations inherently introduce local stiffness discontinuities that govern stress redistribution, interlaminar damage initiation, and influence wing mass distribution and balance constraints. Given the large number of ply terminations in

aircraft composite structures, detailed optimization of each region is computationally impractical during preliminary design. Therefore, efficient numerical assessment methods are required to evaluate stiffness-transition-driven damage mechanisms. This study develops finite element analysis with progressive damage modeling to investigate the influence of laminate architecture on stiffness redistribution, damage evolution, and structural response in tapered composite panels under static and low-velocity impact loading.

2. Methodology

The structural response of composite laminates containing ply drop-off regions was investigated using finite element analysis performed in ABAQUS/CAE v6.14 . The composite panel geometry consisted of thick, tapered, and thin laminate sections with overall dimensions of 150 mm × 100 mm × 1.5 mm. The taper region was designed using a 1:20 slope and a maximum ply drop ratio of 2/3 to satisfy aerospace manufacturability requirements while minimizing abrupt stiffness transitions . The laminate architectures were initially defined using the stacking sequence [0/90/45/-45/90/0]s and ply-curved termination configurations reported as favorable in previous studies . Material properties corresponding to M55J/914 carbon/epoxy prepreg laminates were implemented in the numerical model. SC8R continuum shell elements were employed to accurately capture through-thickness stress redistribution and local stiffness variations within the taper region. Interlaminar damage initiation and propagation were modeled using COH3D8 cohesive elements combined with the Quadratic Nominal Stress Criterion and the Benzeggagh–Kenane mixed-mode fracture law. Intralaminar failure mechanisms were evaluated using the Hashin failure criteria.
Static analyses were conducted under displacement-controlled loading conditions to evaluate stress concentrations and stiffness redistribution near ply termination regions. Low-velocity impact simulations were additionally performed using a rigid hemispherical impactor in accordance with ASTM D7136 impact configurations. To enhance confidence in the numerical predictions, an independently developed MATLAB-based progressive damage framework was employed to verify the ABAQUS predictions of stiffness degradation and damage evolution.

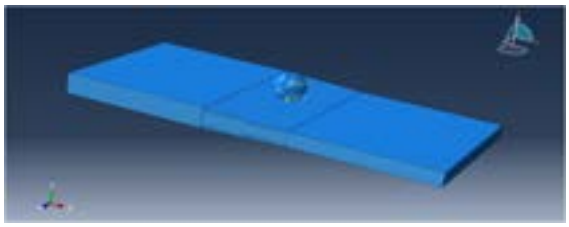


Figure 1. *The FEM Model*

3. Results / Conclusions

The numerical results demonstrate that ply drop-off regions strongly influence local stiffness redistribution. Significant interlaminar stress concentrations were observed near taper transition zones, especially in laminates with sharper local stiffness gradients. Moreover, local stiffness discontinuities directly affect structural mass distribution efficiency by requiring additional reinforcement in critical regions (affecting wing weight balance and aircraft design requirements). The results showed that laminate architectures with ply curving terminations promoted gradual stiffness transitions and reduced localized delamination

propagation near ply termination regions. Under impact loading, damage initiation was concentrated near regions of abrupt stiffness variation and propagated progressively through interlaminar interfaces. The MATLAB-based progressive damage implementation was used to verify the finite element results. This facilitates evaluation of the trade-off between structural weight reduction, local stiffness optimization, and damage tolerance in aerospace composite wing structures, while reducing reliance on extensive experimental testing.

Efficient computation of the dynamic response for vibroacoustic metamaterials on finite stiffened plates

Daniel Alboldt, Marcel Mecnarowski, Lukas Kettenhofen, Kai-Uwe Schröder
RWTH Aachen University, Germany

1. Introduction / Objectives

Propulsion concepts utilizing unducted rotors, such as open-rotor engines, play a significant role in the development of more sustainable future aircraft. However, the use of these engines comes with the drawback of increased noise levels in the cabin, as airborne rotor noise is transmitted directly to the fuselage structure. Vibroacoustic metamaterials (VAMM), composed of local resonators periodically attached to a host structure (Figure 1), offer a lightweight solution for significantly reducing vibrations in the fuselage structure over a tunable frequency range. Designing those metamaterials requires iterative simulations, resulting in considerable computation time when employing full-scale finite element (FE) models. Computationally efficient modelling methods based on dynamic substructuring and model order reduction already exist for infinite and finite unstiffened plates . The present study extends these approaches to stiffened aircraft fuselage structures.

2. Methodology

Usually, modelling of VAMM uses a single unit cell assembled into an infinite periodic structure by periodic Bloch-Floquet boundary conditions. The unit cell consists of the resonator and a part of the host structure to which it is attached.
In this work, dynamic substructuring is used for modelling finite VAMM structures, with the unit cells being the substructures. On unit cell level, the host structure is modelled based on Kirchhoff-Love plate theory, the resonator as a damped single-mass oscillator. Applying the Craig-Bampton method, interior degrees of freedom (DOF) of the unit cell are reduced by using a truncated set of normal modes, leaving the boundary DOF unaltered. The unit cells are then globally assembled by combining their boundary DOF. The stiffeners are considered in the form of appropriate boundary conditions. After application of the global boundary condition, a global modal reduction step is applied to reduce model size, especially for structures consisting of many unit cells.
To validate the proposed modelling approach, experiments are conducted on stiffened plates with and without resonators. The structure is excited with an electrodynamic shaker system (Figure 1), and the forced vibration response is measured using a 3D scanning laser Doppler vibrometer.



Figure 1. *Stiffened VAMM-Plate for experimental validation of the model.*

3. Results / Conclusions

The modelling approach for stiffened structures is validated using the experimental results. The method is evaluated in comparison to a full-scale model regarding the accuracy of the results and computation time. A significant reduction of the computation time is expected to be reached while maintaining sufficient accuracy. Thus, the new approach will enable a fast design process for VAMM on aircraft structures.

Thermal-Function-Driven Design and Integrity Assessment of Multifunctional Multilayered Sandwich Structures for Aircraft Skin Panels

Xiaohui Chen, Kai-Uwe Schröder
RWTH Aachen University, Germany

1. Introduction

Sandwich structures are widely used as lightweight load-bearing components in aerospace applications. While conventional sandwich structures typically consist of two face sheets and one core layer, multifunctional multilayered sandwich structures (MMSS) extend this concept by combining tailored core and sheet layers into an integrated structure with additional functionalities. Cooling the aircraft outer skin during flight can stabilize the boundary layer and thereby reduce aerodynamic drag . To realize this function, an MMSS can serve as a load-bearing aircraft skin panel in which coolant flows through a dedicated core layer to reduce outer skin temperature. Since the cooled layer should not affect inner structures, an insulation layer limits heat transfer. However, the integrated design of such thermal-function-driven load-bearing sandwich structures remains insufficiently addressed. This work develops and assesses a novel MMSS to fulfil cooling, insulation, and mechanical requirements through calculation and simulation of layer-wise thermal behaviour and thermo-mechanical integrity.

2. Methodology

The methodology starts from a representative MMSS configuration, as illustrated in Figure 1. The considered structure consists of three sheet layers and two core layers. The upper core layer is designed as either a TPMS or corrugated structure. Due to the open and continuous

channels within these core architectures, coolant can pass through the structure and interact thermally with the outer face sheet . The lower core layer is considered as a lattice structure, which is investigated with respect to its potential to reduce heat transfer toward the inner side.
Based on this layout, analytical and numerical models are developed to assess the thermal behavior of the individual layers and the integrity of the complete MMSS. First, simplified thermal-resistance models are established to estimate the main heat-transfer paths through the multilayered structure, including heat extraction by the cooling core and through-thickness heat transfer toward the inner face sheet. The TPMS and corrugated cooling-core concepts are then analyzed using conjugate heat-transfer simulations. In these simulations, coolant flow, pressure drop, convective heat transfer, and the resulting outer face sheet temperature distribution are evaluated as functions of core topology, channel size, relative density, and mass-flow rate.
In parallel, the lattice core is represented by homogenized effective thermal-conductivity models and finite-element thermal simulations to quantify its insulation effectiveness. The influence of relative density, strut geometry, void fraction, and possible low-conductivity media is considered. The layer-specific models are subsequently assembled into a complete sandwich model to predict through-thickness temperature gradients, interface heat fluxes, transient thermal response, and the interaction between cooling and insulation effects.

Finally, thermo-mechanical finite-element analyses are performed by combining the calculated temperature fields with representative mechanical load cases. Particular attention is given to thermal stresses, face-sheet deformation, core–face load transfer, and interlayer bonding regions. Parametric studies are used to identify design windows in which sufficient surface cooling and thermal decoupling can be achieved while maintaining the stiffness and structural integrity of the complete MMSS.

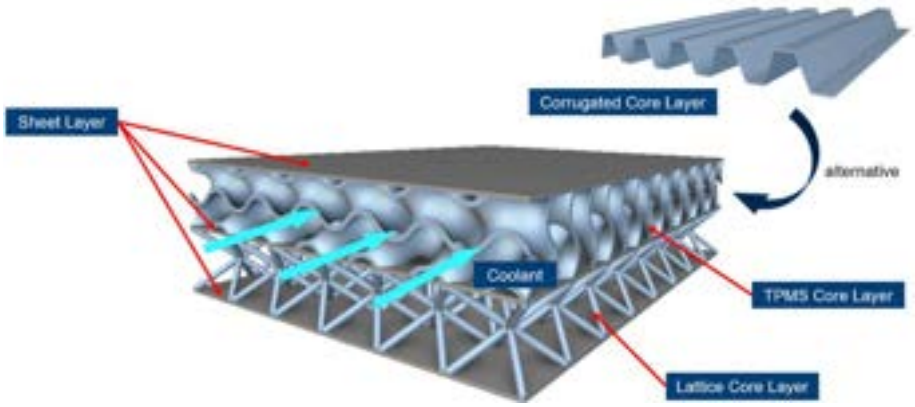


Figure 1. *Schematic concept of the proposed multifunctional multilayered sandwich structure (MMSS).*

3. Results

The expected outcome is a modelling workflow that links layer-wise thermal functionality with the integrity assessment of the complete MMSS. The calculations and simulations will indicate how TPMS or corrugated cooling cores affect the achievable outer surface temperature

reduction, while the lower lattice core limits heat transfer toward the inner structure. By combining these layer responses in a coupled sandwich model, critical thermal gradients, interface heat fluxes, and thermo-mechanical stress concentrations can be identified. The resulting design criteria will support the selection of promising MMSS configurations for thermally functional aircraft skin panels. In contrast to conventional sandwich concepts, the proposed approach treats cooling, insulation, and load-bearing behavior as interacting functionalities within one structural system, thereby contributing to the development of integrated lightweight structures for future aircraft applications.

Aviation in Transition: Bridging Engineering, Operations and Policy

Chaired by:
Mr. Laurent Joly (ISAE-SUPAERO, France)

GHIST: A Geospatial Decision-Support Framework for Hydrogen Aircraft Integration into European Flight Networks

Ayodeji C. Akinola[1] Thomas Feuerle[1], Peter Hecker[1], Marc Launer[2]
[1] Institute of Flight Guidance, Germany
[2] Boeing Deutschland GmbH, Germany

1. Introduction / Objectives

The decarbonisation of European aviation requires more than aircraft technology readiness; it requires coordinated alignment between LH_2 aircraft capability, renewable-H_2 production, airport infrastructure, supply logistics and flight-network structure. Existing studies typically address these domains separately: energy studies estimate hydrogen production potential, airport studies assess infrastructure requirements, and route-network studies apply aircraft range constraints without fully representing hydrogen availability or hub suitability. This creates a planning gap for identifying credible early deployment corridors and H_2-ready airports . This work presents GHIST (Geospatial Hydrogen Integration Simulation Tool), an integrated scenario-based geospatial decision-support framework linking renewable-resource sampling, levelized cost of hydrogen (LCOH) estimation, Hydrogen Readiness Index (HRI) screening, aircraft range filtering and route optimization. The objective is to provide a reproducible technical basis for selecting candidate airport hubs, feasible city-pairs, supply areas and phased deployment strategies for European hydrogen aviation.

2. Methodology

GHIST is implemented as a modular Python geospatial simulation framework for assessing hydrogen-aircraft deployment feasibility across European flight networks. The framework consists of three coupled layers: data, analysis and output. The data layer integrates renewable-resource rasters, airport and route databases, aircraft performance assumptions, hydrogen techno-economic parameters and energy-policy indicators. Solar and wind potential are represented using Global Solar Atlas and Global Wind Atlas inputs, while airport and route structures are derived from OpenFlights.
For each scenario, GHIST samples renewable-resource potential around selected airports or regions and estimates location-specific hydrogen production cost using an LCOH model. The

model incorporates electrolyser CAPEX, renewable capacity factor, operating cost, conversion efficiency, discount rate, deployment year and technology-learning assumptions. A hybrid renewable-production case is represented using solar-day and wind-night operation to capture complementary resource availability.
Airport and country suitability are evaluated through the Hydrogen Readiness Index (HRI), which aggregates technology, resource, infrastructure, policy, economic and operational-market indicators. Criteria are normalized to [0,1], weighted and classified into readiness classes A–E. This enables GHIST to distinguish routes that are geographically reachable from routes that are also plausible under airport, infrastructure and supply conditions.
Route feasibility is evaluated using great-circle distances between origin–destination airport pairs and hydrogen-aircraft range envelopes up to 6,500 km. Routes are classified as direct, one-stop or infeasible. Candidate stopovers are ranked using distance efficiency and HRI thresholds, ensuring that selected refuelling nodes are both geographically useful and deployment-relevant. The fleet-network module evaluates aircraft replacement scenarios by combining route coverage, hub selection, refuelling-node availability and CO_2-reduction potential. Outputs include renewable-H_2 production maps, LCOH distributions, HRI/readiness maps, supply-area maps, route-feasibility classifications and network-deployment dashboards.

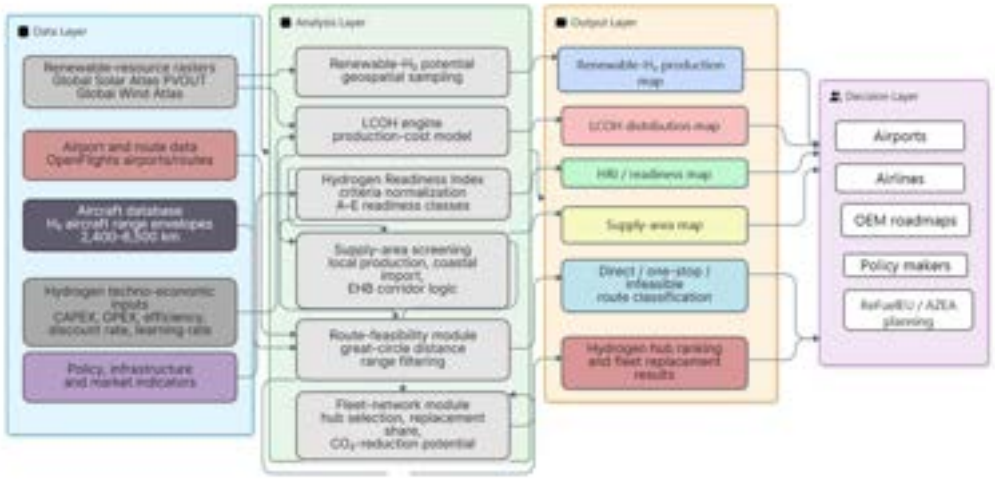


Figure 1 GHIST workflow for hydrogen-aircraft integration into European flight networks.
The framework links renewable-resource assessment, techno-economic hydrogen modelling, HRI-based readiness screening, supply-area evaluation, route-feasibility analysis, and fleet-network deployment within a unified geospatial decision-support environment.

3. Results / Conclusions

A European intra-continental case study demonstrates GHIST's ability to couple hydrogen economics, airport readiness, and aircraft range constraints into a network-deployment assessment. For a 2,700 km H_2 narrowbody concept, most major city-pairs are directly feasible, while peripheral routes require HRI-filtered intermediate refuelling at high-connectivity hubs such as FRA, CDG, AMS, MAD, and LHR, consistent with existing findings on early LH_2 integration hubs . Under the hybrid renewable-production scenario, 2026 LCOH values vary spatially, with lower costs in Southern Iberia, Iceland, and Nordic regions than in less favourable Central and Eastern European regions. Under a 2035 learning scenario,LCOH converges toward approximately €2.6–3.2/kg, while higher-cost regions may require coastal

import terminals and European Hydrogen Backbone corridors. Fleet-network analysis using AMS, FRA, CDG, CPH, OSL, MAD, and LHR as hubs indicates that an H_2-A320 could replace about 10% of intra-European flights, increasing to 14% for an H_2-A332 concept.

Tailoring Aviation Decarbonisation Roadmaps: Advancing AeroMAPS Towards Highly Customisable Scenario Modelling

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1. Introduction

Aviation accounted for around 2.6% of global CO_2 emissions in 2019 and close to 4% of effective radiative forcing once non-CO_2 effects are included . Reducing its impact can be achieved by efficiency gains, enhanced operations, alternative aviation fuels, demand management or offsetting, with the deployment of some options depending heavily on policy support . Prospective transition scenarios have become a key decision-making tool , and open-source frameworks have emerged to assess them across technical, environmental and economic dimensions, such as AeroMAPS . However, the latter initially relied on a predefined set of energy carriers and production pathways, treated air traffic as four predefined, immutable segments, and was confined to a fixed geographical scope (either global or local), limiting its adaptability to user-specific assumptions or multi-regional analyses. This work introduces recent developments making AeroMAPS' energy, market and fleet representations fully generic and enabling multi-regional assessment, demonstrated through an illustrative case study.

2. Methodology

AeroMAPS is a Python framework structured to model air transport transition and its technical, environmental and economic impacts . The framework inherits from a multidisciplinary design and analysis optimisation backbone supporting model couplings and scenario optimisation . This contribution presents three evolutions of the framework, summarised in **Figure 1**.

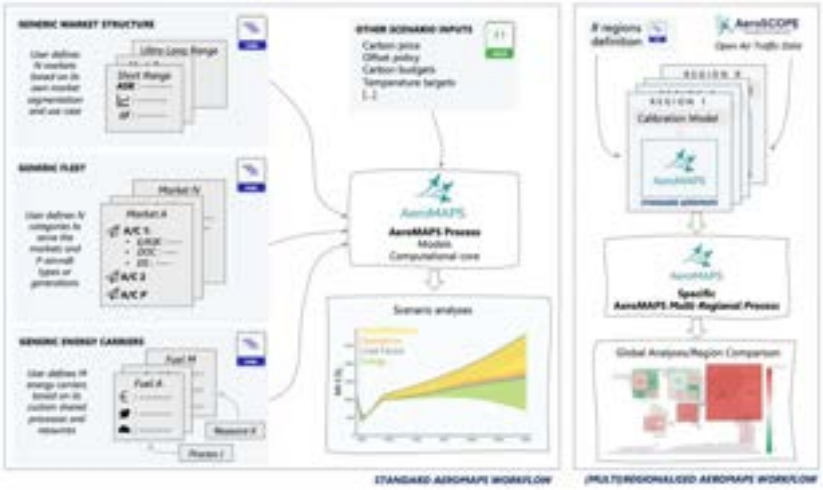
First, a fully generic energy model is introduced. Users define an arbitrary number of energy carriers, each built from custom production processes and shared resources, and characterised by their own techno-economic and environmental parameters, either by focusing on the product itself or by describing its production process. This enables configurations unavailable in earlier versions (for instance power-and-biomass-to-liquid pathways) and it lets users choose their own modelling approach. Second, a generic market model lets users partition traffic into an arbitrary number of markets following their own segmentation, each with its own demand profile, load factor and other operational assumptions. Third, the existing AeroMAPS fleet model has been revised to reflect the generic market, allowing users to define the characteristics of the aircraft generations serving a given market.

These three blocks are supplied through user-configured input files *(.yaml)* and combined with other inputs in the AeroMAPS computational core. Building on this, a novel mode lets users simulate multi-region scenarios: regions are defined and calibrated using open air traffic data and are simulated with the standard AeroMAPS workflow before aggregation

through a dedicated multi-regional process.

3. Conclusion

These developments pave the way for a whole set of new analyses with AeroMAPS. For instance, the multi-regional mode supports ongoing work on global policy consistency analysis and cross region comparison, capturing the effect of differentiated regional



policies. The generic energy, market and fleet models further allow scenarios that were previously impossible to represent within the framework: in particular, the introduction of new fuel types is

Figure 1. *Standard (left) and multi-regional (right) AeroMAPS workflows.*

now effortless. It also aims to reinforce AeroMAPS' interfacing capabilities to serve as a reference platform for modelling transition scenarios, for both academics, institution and industry actors, who will be able to easily replicate the workflows they use.

Fleet-Level Assessment of Multi-Fuel Aircraft in the European Flight Network

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[2]Manchester Metropolitan University, UK

1. Introduction / Objectives

Hydrogen (H_2) is considered a promising long-term energy carrier for aviation regarding decarbonization . However, a coordinated development of H_2-powered aircraft and the corresponding airport and energy infrastructure remains a major challenge, delaying their adoption. The research project "**HOPE** (**H**ydrogen **O**ptimized multi-fuel **P**ropulsion system for clean and sil**E**nt aircraft)" addresses this challenge by assessing an integrated propulsion system capable of operating with fossil fuel, sustainable aviation fuel (SAF), and H2. An aircraft equipped with such a propulsion system should support a smoother aviation energy transition towards greener propulsion technologies while mitigating risks associated with limited hydrogen infrastructure availability.

The main objective of this study is to perform a holistic, scenario-based assessment of the operational potential of such multi-fuel aircraft within the European flight network. Hereby, key socio-economic and operational factors, including air traffic demand evolution, fleet retirement and renewal, fuel costs, and policy-driven fuel mandates, are considered.

2. Methodology

The study applies the Bauhaus Luftfahrt in-house air transport system (ATS) assessment framework to evaluate the operational potential of multi-fuel aircraft within the European flight network and focuses on the long-term fleet-level effects until 2070. The ATS framework consists of three main elements: scenario creation, data preparation, and fleet optimization. First, exploratory scenarios are developed following a structured scenario creation process including problem definition, uncertainty-impact analysis, and consistency analysis. Hereby, key socio-economic, technical, and environmental drivers influencing deployment of hydrogen in aviation are identified in expert-based workshops and translated into consistent future scenarios. The resulting scenario fact sheets define assumptions regarding air traffic demand evolution, fuel prices, hydrogen infrastructure availability, fleet retirement, aircraft production rates, and future fuel mandates.
Second, these scenarios are integrated into the ATS assessment framework. For this purpose, all elements of the scenario fact sheet must be quantified and translated into model inputs, including air traffic demand, initial fleet, fuel supply pathways, and aircraft performance characteristics.
Finally, fleet development and allocation, as well as technology adoption are determined using a linear programming model. The optimization minimizes overall block energy (BE) consumption and/or the energy component of direct operating costs (DOC) under the given scenario constraints while determining the optimal fleet composition and market penetration potential of multi-fuel aircraft over the considered time horizon.

3. Results / Conclusions

The ATS framework provides fleet-level outputs including fleet composition and its evolution, BE consumption, fuel usage, and emission inventories for selected scenarios over the considered time horizon until 2070. Simulation results compare the performance of a reference aircraft (A320neo-class), a next-generation conventional aircraft (HOPE-BL) , and the HOPE multi-fuel aircraft at fleet level. The three aircraft are depicted in Figure 1.



Figure 1 *HOPE aircraft technologies (adapted from).*

The preliminary results indicate a potential reduction in BE consumption of up to 22% by 2070 through the deployment of the HOPE-Baseline aircraft at fleet level. The introduction of the HOPE multi-fuel aircraft operated with maximum hydrogen utilization achieves a BE reduction of up to 17% relative to the reference aircraft, while showing an increase of approximately 7% compared to the HOPE-BL configuration. However, these preliminary results demonstrate a strong sensitivity to the pace of hydrogen infrastructure deployment which will be further assessed within this study. Furthermore, climate impact of selected scenarios is currently being assessed.
Overall, the study highlights the added value of an integrated ATS assessment framework for evaluating long-term fleet evolution and assessing the operational potential of emerging aircraft technologies supporting climate-neutral aviation strategies.

A Roadmap for the Reliable Adoption of Wide Bandgap Power Electronics in Electric Aircraft Propulsion

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1.Introduction

Electric aviation requires wide bandgap (WBG) power electronics to achieve the power densities necessary for multi-megawatt propulsion. However, existing standards account only for either the unique stressors of the aerospace environment or the suitability of WBG power electronics for terrestrial applications. Specifically, the exponential increase in terrestrial neutron flux and the reduction in dielectric strength at cruising altitudes needs to be carefully studied for WBG power electronic components. The main objective of this study is to propose a multi-tier reliability roadmap that bridges the gap between device-level physics and airworthiness requirements of power systems in future electric aircrafts. This research paper introduces an innovative conceptual scientific roadmap, integrating physics-of-failure simulations models with mission-specific constraints. Unlike the current state of the art, which relies on industrial standards, mostly suitable for either terrestrial or space applications, this framework provides a methodology to quantify reliability margins, such as Single-Event Effect (SEE) thresholds (influenced by cosmic radiation) and Partial Discharge (PD) thresholds (influenced by high-frequency and high-speed operations) , specifically for high-altitude flight profiles.

2.Methodology

The proposed conceptual roadmap utilizes a nested three-tier reliability framework designed to guide the development and certification of WBG power electronics for electric aircraft propulsion. The relationship between established industry standards, advanced simulation tools, and the critical reliability gaps that exist towards certification of aerospace power system components are highlighted in this roadmap, as shown in Figure 1.

- WBG Device Physics: At the foundational level, the focus is on the Silicon Carbide (SiC) or Gallium Nitride (GaN) semiconductor die. In this stage, Technology Computer Aided Design (TCAD) for physics-level modeling and Simulation Program with Integrated Circuit

Emphasis (SPICE) for circuit-level transients is utilized. While JEP 194/195 is highly relevant for gate integrity, this framework identifies a lack of time-to-failure models and a poor understanding of how neutron displacement interacts with Bias Temperature Instability (BTI) over long flight hours.

- Electric Powertrain: The intermediate level addresses power module and converter integration, encompassing packaging, cooling, and topologies like 2-Level Voltage Source Inverters (2L-VSI) and 3-Level Neutral-Point-Clamped (3L-NPC) evaluated alongside Field-Oriented Control (FOC) for PMSM drives. Using PLECS and Ansys tools (Q3D, SIWave, Mechanical), it analyzes switching behavior, parasitic ringing, electro-thermal coupling, and thermo-mechanical fatigue. Unlike single device studies, this level captures how mission-dependent load profiles dictate systemic interactions among converter operation, control dynamics, thermal management, and electric machine loading, directly influencing junction temperature dynamics and cycling stress. Consequently, the thermal system critically governs power density, efficiency, and lifetime. Finally, while automotive standards provide a methodological basis, aerospace translation demands additional accounting for altitude-dependent insulation coordination, reduced ambient pressure, and aircraft-specific reliability constraints.
- Aviation System Integration: The topmost level oversees the entire propulsion system within the aircraft environment. This level prioritizes RTCA-DO160G , IEC-62396 and FIDES guide for environmental and radiation compliance. Simulation tools such as COMSOL and Ansys Maxwell are critical here for modeling high-altitude effects. The identified gaps highlight a major deficiency in standardized responses to WBG-specific dV/dt transients and the application of Paschen's Law for high-frequency switching at altitude.



Figure 1. Three-tier conceptual reliability roadmap for WBG power electronics' integration into the electric propulsion system.

3.Conclusions

The primary takeaway from this work is that terrestrial standards are fundamentally insufficient for the safety-critical rigors of electric aviation, since an WBG power inverter in the aircraft propulsion system operates at a significantly higher power density compared to terrestrial applications. This conceptual study highlights that standard 80% voltage derating is

inadequate at cruising altitudes, where a conservative 50% derating might be essential to mitigate accelerated neutron-induced failures . Additionally, simulations might reveal a 40% reduction in PD Inception Voltage (PDIV) at cruise pressures, exposing a blind spot in current IEC 62477 guidelines. This reliability roadmap is also designed to identify latent failure modes, like radiation-induced gate degradation, that are often overlooked. Bridging device physics, powertrain packaging, and system integration via this multi-tier methodology provides a predictive roadmap for reliability. Ultimately, this approach addresses the current risks and gaps towards certification of aerospace power system components and provides the scientific foundation necessary to evolve legacy benchmarks into a comprehensive, aerospace-specific standard for high-voltage electric propulsion.

Operational Efficiency through Aircraft Sharing: A Tactical Planning Perspective

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[2]Technical University of Munich, Germany

1. Introduction / Objectives

Aviation should urgently reduce its environmental impact and has committed to achieving net-zero CO_2 emissions by 2050 in support of the Paris Agreement. While many technological solutions require lengthy development cycles to achieve system-wide benefits, operational innovations can deliver short-term efficiency gains by reducing redundant flights and increasing aircraft utilization. In this study, we investigate an operational aircraft-sharing concept in which participating airlines jointly use aircraft to operate their flights, thereby enabling more efficient aircraft rotations and reducing redundant capacity. Building on previous work on strategic network design under aircraft-sharing scenarios , , this study shifts the focus to the tactical planning level, addressing timetable development and aircraft rotation planning. In contrast to previous studies that have explored incremental improvements of existing schedules, mainly focusing on enhancing profitability for airlines , , the present study adopts a system-level perspective by examining fleet-size reduction to lower aviation's environmental footprint.

2. Methodology

To evaluate the operational potential of aircraft sharing, new flight schedules are generated from scratch and compared under sharing and non-sharing scenarios. Due to computational complexity, airline scheduling problems are commonly split into frequency planning, fleet assignment, timetable development, and aircraft rotation planning . This study focuses on the latter two. For this purpose, two mixed-integer linear programming models are developed. The first model addresses the timetable development and generates feasible timetables. Its objective is to minimize the number of physical aircraft required to operate the schedule while satisfying demand. The constraints ensure that each flight is assigned to one time period, airport capacity limits hold, and flow conservation holds across the network over all time periods. This ensures cyclic feasibility, meaning that, at each airport, the number of aircraft of each class at the end of the time horizon equals the number available at the beginning. Subsequently, the second model addresses aircraft rotation planning by assigning aircraft to the resulting flights. We introduce the concept of a flight chain, defined as a

temporally feasible sequence of flights operated by the same aircraft. The model uses binary decision variables to assign flights to flight chains and link these chains across consecutive planning horizons, ensuring cyclic feasibility over multiple weeks. Its objective is to minimize the number of flight chains, implicitly reducing the number of aircraft required to operate the complete schedule. The constraints ensure that each flight is assigned to one flight chain, that the temporal ordering of flights within each chain is feasible, and that a bijective mapping between chains in consecutive weeks is established.
The approach is applied to a network covering the European, North American, and transatlantic markets, with 668 airports and 54,362 origin-destination pairs. Due to this large-scale setting, heuristic solution approaches are developed to solve the two exact formulations in a computationally tractable way. Current efforts focus on enhancing the initial construction heuristic through an additional improvement heuristic, aiming to increase solution quality while maintaining computational tractability.

3. Results / Conclusions

Applying the given scheduling approach reveals that aircraft sharing can reduce overall flight activity in the EU - NA network and lower the required fleet size by 10,8%, thereby potentially alleviating congestion at both airspace and airport levels. In addition, the results suggest that aircraft sharing can improve fleet utilization, as it becomes more balanced under the sharing scenario. While the non-sharing case leads to an uneven use of fleet groups, aircraft sharing enables more flexible allocation across the network (Figure 30). This suggests that aircraft sharing may lower fleet acquisition requirements by enabling the same demand to be served with fewer aircraft.

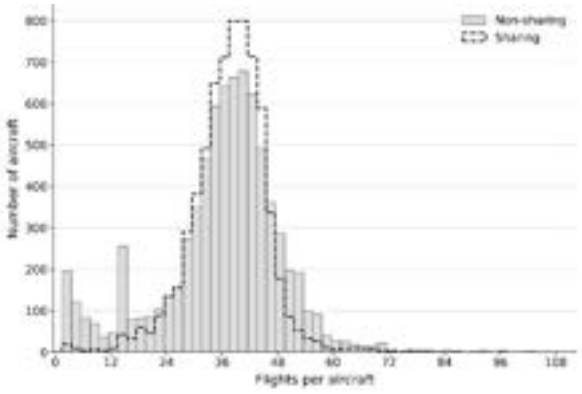


***Figure 30**. Distribution of fleet utilization*

Business Impact Assessment of Environmental Decision-Support Tools for Aviation and Innovative Air Mobility

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Future Needs Management Consulting LTD, Cyprus

1. Introduction / Objectives

Decarbonizing aviation remains a critical challenge, with digital tools emerging as the most

immediately deployable levers ahead of advanced propulsion technologies and sustainable aviation fuels . Innovative Air Mobility (IAM) faces additional sustainability barriers, including noise, weather resilience, and societal maturity issues, all of which hinder viable business model development . This study builds upon the EU RefMap project , which developed a modular suite of environmental modeling tools designed to support sustainability-focused decision-making across both aviation and IAM, addressing challenges such as non-CO2 emissions, noise impact assessment, and human exposure. Using a previously established Minimum Viable Product (MVP) of the toolset, this work examines how stakeholder-prioritized tool features can inform and reshape business models in both sectors. The goal is to translate modeling capabilities into actionable, economically viable strategies for improving sustainability across short (0–2 years), medium (2–5 years), and long-term (5+ years) horizons.

2. Methodology

The research methodology employed an integrated business model impact framework, structured around the Venture Pyramid concept by Göcke & Weninger (2021) , on current aviation and IAM sector business models. Our process included 5 steps: market and policy landscape assessment, identification of stakeholders of current aviation and IAM business models, impact of availability of Refmap project tools on the value proposition and problem-solution fit of current business models, and tool scalability requirements to meet additional user needs, as illustrated in **Figure 1**. The Business Model Canvas (Osterwalder & Pigneur) was employed to map the current business models of the two sectors for 4 types of stakeholders: airport operators, Air Navigation Service Providers (ANSPs), drone operators, and smart city authorities. These business models were sourced from literature review describing representative real businesses. The impact of the Refmap tools on the business models were validated through 15 semi-structured

interviews with domain experts and industry representatives. Given the low Technology Readiness Level (TRL) of the available tools and the absence of a consolidated regulatory framework, the impact evaluation focused on three core canvas elements: value proposition, cost structure, and revenue streams. Interview participants evaluated each tool's relevance across two dimensions, impact significance and expected time horizon, and findings were



Figure 1. *An Integrated Business Model Impact and Validation Framework for Sustainable Aviation and IAM.*

synthesized into a Viability Impact and Timeline Matrix, illustrated in **Figure 2**. This approach was consistently applied across all 4 stakeholders groups.

3. Results / Conclusions

Critical parameters for early adoption of digital environmental modelling tools across commercial aviation and IAM were identified. Policymakers and regulators emerge as primary anticipated adopters, expected to use these tools to mature regulation, given their central role in establishing incentive structures for market uptake. Airlines, operating under tight profit margins, find the most immediate value in fuel cost savings, which account for approximately 30% of total operating expenditure. Airport operators benefit most from accelerated, reliable permitting processes enabled by air pollution and noise impact modelling. UAS and drone operators gain value from proof-of-safe-flight capabilities, supporting faster regulatory approvals through predictions of wind, weather, noise, and visual pollution impacts. Non-CO_2 regulatory requirements make preparatory measures for baseline data access an urgent priority. Operational adoption constraints were also identified, enabling product-market-fit assessment beyond desk research alone. Overall, aligning modelling capabilities with stakeholder-specific incentives can accelerate both sectors' transition towards a more sustainable future.

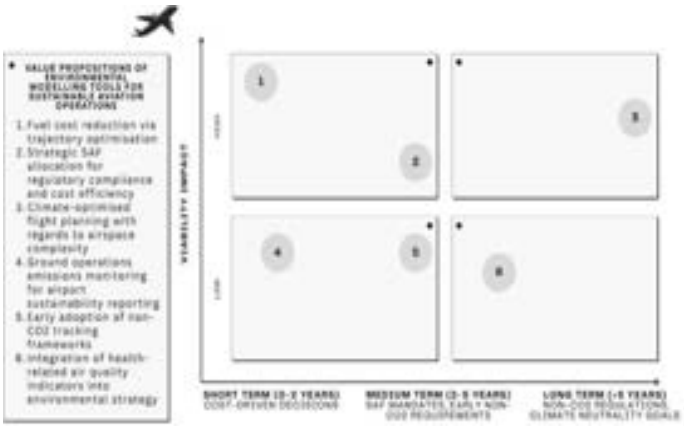


Figure 2. *Viability Impact and Deployment Timeline of Environmentally Oriented Value Propositions for Airlines: A Stakeholder Validation Perspective.*

Poster Section

'Multi-Fidelity Design and Aero-Thermal Integration of a High-Performance Heat Exchanger for Fuel Cell Aircraft

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1. Introduction / Objectives

Achieving net-zero greenhouse gas emissions and enabling a climate-neutral aviation system in Europe by 2050 requires significant advances in propulsion and thermal management technologies. Hydrogen as an aviation fuel offers the key advantage of eliminating in-flight CO_2 emissions, while fuel cell propulsion enables emission-free operation, avoiding NOx and particulate matter. However, increasing fuel cell power leads to substantial thermal loads that must be effectively dissipated. In particular, the small temperature difference between the fuel cell system and ambient air presents a major design challenge. This combination results in large heat exchanger systems, increasing drag and reducing overall aircraft efficiency. These constraints drive the development of compact, lightweight, and highly

efficient heat exchanger solutions for next-generation sustainable aviation systems.

2. Methodology

The heat exchanger design is developed through a multi-fidelity, system-driven methodology combining preliminary sizing, detailed design, integrated Multiphysics verification which is illustrated in figure 1. First, an in-house low-fidelity sizing tool is applied to determine optimal core dimensions based on selected mission points, thermal duty, pressure losses, mass, manufacturability constraints, and system-level integration requirements. This enables rapid exploration of the design space and identification of feasible geometries.



***Figure** 1: Multi-fidelity design and integration workflow*

The resulting configuration is translated into detailed CAD models, including core and manifold geometries. Performance verification is conducted using high-fidelity conjugate heat transfer simulations to evaluate coupled thermal and fluid dynamic behavior and to quantify deviations from low-fidelity predictions.

Structural integrity is assessed using finite element method (analyses under proof, burst, and vibratory load conditions in accordance with relevant aerospace standards. Attention is given to stress concentrations in flange regions and fatigue performance under cyclic loading. Sensitivity to mounting boundary conditions is also evaluated to identify potential structural risks and mitigation strategies.

System-level integration is addressed through computational fluid dynamics studies of the heat exchanger embedded within the nacelle environment. A parametric investigation of placement parameters (inclination angle, axial location, and vertical offset) is performed to quantify trade-offs between aerodynamic drag and thermal performance. An optimal configuration is identified that balances these competing effects, ensuring sufficient heat rejection while minimizing aerodynamic penalties.

The integrated multi-fidelity workflow ensures consistent convergence between thermal, structural, and aerodynamic requirements, resulting in a manufacturable, high-performance heat exchanger tailored for advanced aviation propulsion systems.

3. Results / Conclusions

This study presented a multi-fidelity methodology for the design, analysis, and integration of a high-performance aircraft heat exchanger. The combined use of low-fidelity sizing, high-fidelity conjugate heat transfer simulations, structural FEM analysis, and CFD-based aero-thermal integration enabled a robust multidisciplinary design process. Results demonstrate strong coupling between thermal performance, structural constraints, and aerodynamic effects, with heat exchanger placement significantly influencing overall system efficiency. An optimal configuration was identified that balances heat rejection capability with minimal aerodynamic penalty while satisfying structural requirements. The proposed methodology provides a scalable framework for the development of compact and efficient thermal management systems for future low-emission aviation applications.

Acknowledgment: This work is supported in part by European Union with Clean Aviation Project HEROPS (Hydrogen-Electric Zero Emission Propulsion System) under Grant 101140499.

A Multimodal Graph Framework for Air-Rail Connectivity Analysis and Disruption Simulation

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1. Introduction / Objectives

Multimodal transport integration is often hindered by fragmented coordination between air and ground transport service providers (TSPs) during irregular operations. This study introduces TimeSync, a core functionality within the Travel Wise solution architecture designed to support flight-to-rail synchronization analysis and to surface intermodal alternatives when disruptions occur. While European policy prioritizes air-to-rail modal shifts, the practical availability of integrated alternatives remains limited . By addressing the critical barrier of disparate data formats and harmonizing rail (GTFS) and air (EuroControl R&D) feeds, TimeSync enables analysis of intermodal connectivity at hub airports — Bologna (BLQ) is used as a demonstration case — and the simulation of user-specified disruption scenarios. The objective is to move beyond passive information sharing toward an explicit, graph-based catalogue of feasible and near-feasible intermodal routes that can be queried to suggest alternatives when operations are disrupted.

2. Methodology

The development of the TimeSync functionality follows a structured, multi-phase methodology, focused on harmonizing connectivity data and operationalizing it through graph-based modeling .

Phase I: Conceptual Alignment and Data Harmonization

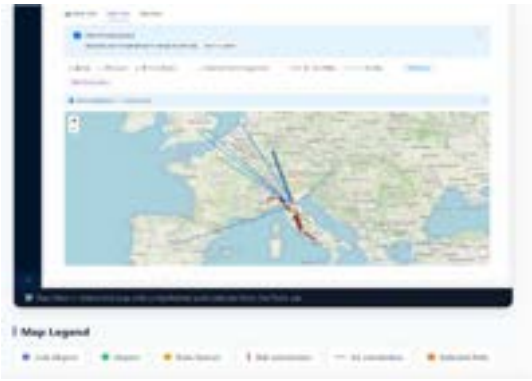
The initial phase aligns terminology across air and rail domains . A unified data-ingestion layer addresses the diversity of formats — GTFS for rail and EuroControl R&D CSV for air — through dedicated adapters that emit a common set of stations and timetabled connections, written

into a single Sparksee graph . Airports and nearby train stations are merged into hub nodes within a configurable radius (default 6 km); for example, Bologna Airport (BLQ) and Bologna Centrale are treated as one transfer point. The result is a unified multimodal graph rather than mode-specific layers, providing the substrate on which connectivity is subsequently analysed.

Phase II: Operationalization through Graph-Based Routing
Connectivity is operationalised by enumerating multimodal routes through the graph using forward, backward, and mode-agnostic Connection Scan Algorithm (CSA) passes anchored at each hub . The output is a route catalogue containing rail→hub→air, air→hub→rail, single-mode rail, and single-mode air journeys, classified as PRIMARY (best feasible), ALTERNATIVE (substitutable single- or two-leg variants), or gap (near-feasible journeys annotated with the signed minutes of schedule shift that would make them feasible). Routes are grouped by (origin, destination, mode pattern) so that substitutable journeys for any O–D pair are explicit. Summary statistics — route counts by mode pattern and status, with min/avg/max durations and transfer times — characterise connectivity at the hub.

Phase III: Architectural Implementation (TimeSync)
The framework is delivered as a web application backed by the precomputed route catalogue. Through the TimeSync interface, TSP users browse hub connectivity on interactive maps and tables and drive the disruption module by specifying a scenario (cancellation, delay, early departure, extended dwell, or missed connection) on a chosen leg. The engine filters the catalogue against the scenario and the surviving alternatives are surfaced back to the user as ranked routes, map overlays, and gap indicators, splicing replacement legs without recomputing journeys. Live-feed integration with operational data sources is foreseen as future work within Travel Wise.

3. Results / Conclusions



A demonstration run on the Bologna hub, using Trenitalia GTFS rail data and an Air France EuroControl R&D dataset, exercises the full pipeline end to end: ingestion, hub merging (BLQ + Bologna Centrale), CSA-based route enumeration, and disruption simulation through the web interface. The route catalogue makes intermodal alternatives explicit at the hub, including near-feasible 'gap' routes that quantify the small schedule shifts required to enable additional connections. TimeSync gives TSPs a foundation for evaluating disruption impacts and surfacing intermodal alternatives to operators and passengers, supporting the SESAR vision for integrated multimodal nodes and improving access to the airport. Ongoing work targets larger-scale validation with operational TSP data and integration with live data feeds.

Acknowledgment: This research was co-funded by Europe´s Rail Joint Undertaking, SESAR

Joint Undertaking and European Commission, within the project "TRansformation of AViation and rAilway soLutions toWards Integration and SynergiEs (Travel Wise) under grant number 101178579).

Synergistic Design of a Strut-Braced Wing Aircraft with Natural Laminar Flow for Energy-Optimal Long-Range Operations

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1. Introduction / Objectives

Reducing aviation's energy consumption is essential for achieving long-term sustainability targets. As incremental improvements to the conventional tube-and-wing (TAW) configuration approach diminishing returns, unconventional concepts such as the strut-braced wing (SBW) offer a step change in aerodynamic efficiency through substantially higher aspect ratios and wing spans at reduced structural weight penalties. This study, conducted within the German LuFo project UniSELECT, investigates the synergistic combination of a SBW configuration with a design cruise Mach number of M 0.7, natural laminar flow (NLF) on the wing, a reduced design range, and a high-density all-economy cabin layout for the long-range segment, targeting a passenger capacity competitive with today's Airbus A350-900. The objective is to quantify the combined energy savings and to identify the design optimum by systematically varying Mach number, range, and cabin density against multiple baselines, using energy consumption as the figure of merit.

2. Methodology

All UniSELECT aircraft configurations are designed and sized using UNICADO , a collaborative conceptual aircraft design environment developed by leading German aerospace universities. UNICADO employs a modular software architecture that facilitates the extensibility and exchangeability of individual design and analysis disciplines. Its core design loop iterates through initial sizing, component design (fuselage, wing, strut, empennage, landing gear, propulsion, and systems), aerodynamic analysis, mass estimation, mission simulation, and performance assessment. Dedicated methods for strut-braced wing (SBW) configurations are integrated across all relevant sizing and analysis modules.
The study investigates a long-range SBW transport aircraft with a single-class, high-density cabin layout equivalent in passenger capacity to the Airbus A350-900. The primary SBW design features a cruise Mach number of 0.7, which enables reduced leading-edge sweep and thereby facilitates extensive natural laminar flow (NLF) on the wing. Design range is set to a value representative of high-frequency long-range route networks, below the range capability of the current A350-900. All configurations share a common entry-into-service (EIS) year, ensuring consistent technology assumptions for structures, propulsion, and systems.

To isolate individual and combined effects of the key design parameters, the following configurations are evaluated:

- A TAW baseline at the target EIS with conventional cruise Mach number, design range, and multi-class cabin, representing a next-generation A350-900 successor.
- TAW and SBW variants, each incorporating single parameter changes: reduced Mach number, reduced range, or high-density cabin, to isolate individual effects.
- A SBW configuration combining all three parameter changes simultaneously.
- Additional SBW and TAW variants with systematic sweeps across Mach number, range, and cabin density to map the broader design space.

Energy consumption per passenger-kilometer serves as a figure of merit, enabling equitable comparison across configurations that differ in design range and seating capacity.

3. Results / Conclusions

Results are presented for the complete set of design variants, quantifying the energy consumption reduction of the SBW configuration relative to both the conventional TAW baseline and the parameter-matched TAW variants at the same entry into service. The parametric decomposition reveals the individual contributions of reduced cruise Mach number, natural laminar flow, reduced design range, and increased cabin density, and quantifies synergistic interactions between these measures at the aircraft system level. A sensitivity analysis across the Mach–range–cabin density parameter space identifies the energy-optimal design point and illustrates the penalties associated with deviations from this optimum. The results demonstrate that co-optimizing configuration, cruise speed, range, and cabin layout yields substantially greater benefits than addressing any single parameter in isolation. These findings provide quantitative guidance for the design of next-generation long-range transport aircraft within the UniSELECT research framework.

Control of a Friction Welding Device mountable on CNC Lathes

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1. Introduction

Friction welding is of particular interest in aerospace manufacturing due to its solid-state nature ensuring superior structural integrity and fatigue resistance. It can be applied to the same or to dissimilar metals, to thermoplastics or even to polymer matrix composites . This paper presents the development of a friction welding device that can be fitted to the tailstock of CNC lathes. It describes the design challenges, modeling, and implementation phases, focusing particularly on a closed-loop control strategy for the welding process.

2. Methodology

The friction welding process kinematic mechanism was translated to a system consisting of a chuck mounted on the lathe's tailstock and moving linearly, as driven by a servo motor through a reduction gearbox. The tailstock chuck is fitted with a high precision piezoelectric load cell. The first workpiece is clamped in this chuck. The second workpiece is mounted on

the lathe's own chuck. Torque and axial force requirements for the welding process were analytically modelled for various materials (e.g., aluminium, PMMA, PA6) including frictional effects and geometric constraints, also considering the required axial movement resolution so as to size the reduction gearbox without overloading the motor. Real-time control of axial welding force in both friction and forging phases of the welding cycle was achieved using a closed-loop feedback system implemented on a standard programmable logic controller (PLC). The brushless servo motor was controlled by a variable frequency drive receiving analogue control signals from the PLC. The latter monitors force continuously over an analogue input as required by the feedback loop to dynamically correct deviations in the targeted force by adjusting the motor speed (angular displacement). The control strategy implements a PID (Proportional-Integral-Derivative) algorithm for force regulation. PID parameters were tuned experimentally using an "adjust and observe" approach to accommodate different welding conditions.

3. Results / Conclusions

Mechanical assembly was installed on a reinforced, modular aluminium base and included an optimized pulley-timing belt system. The final configuration delivered enhanced torque efficiency, minimized system wear, and provided the flexibility to accommodate various welding scenarios, see Figure 1. The controller was capable of maintaining precise force levels throughout the friction and forging phases, as tested for joining polypropylene (PP) rods of 20 mm diameter, see Figure 2. In validation experiments with rotation speed of 500 rpm, friction pressure of 2.9 MPa, forging pressure of 8.8 MPa, friction time of 10 sec and forging time of 18 sec, the maximum load reached at failure in a four-point bending test was 3496 N, i.e. only 5.6% lower than the load of the bulk material (3700 N). This approach offers a cost-effective alternative to standalone welding machines while retaining flexibility and extensibility for future developments towards a smart machine that will ideally be deciding welding conditions autonomously transparently, i.e. with minimal knowledge of material grade and part dimensions.



Figure 1. *The friction welding device (a) CAD model of the device (b) Servo motor, gear reducer in blue, timing pulley mounted behind the tailstock (c) Custom chuck assembly with force sensor*

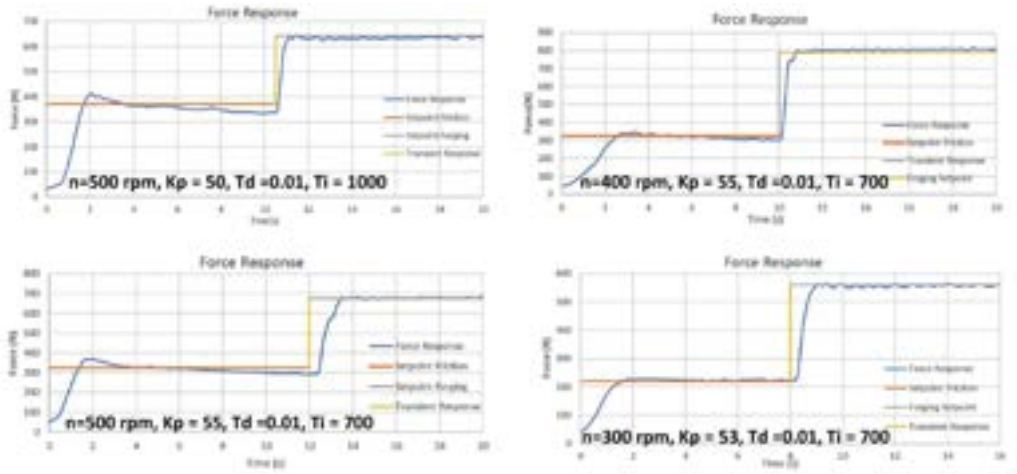


Figure 2. *Indicative response patterns for different PID controller parameters when welding PP for various rotation speeds.*

Environmental Durability of Fiber-Reinforced Polymer Composites for UAV Structures under Thermal, Humidity, and Salt-Spray Exposure: An Integrated Computational-Experimental Framework

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1. Introduction / Objectives

The rapid expansion of unmanned aerial vehicles (UAVs) has enabled a wide range of critical applications such as disaster monitoring, rapid wildfire detection, and emergency response operations. These missions often require aircraft to operate in challenging environments where structural integrity and performance are essential for safe and continuous operation. To meet performance and weight requirements, unmanned aircraft are widely manufactured using fiber-reinforced polymer (FRP) composites due to their high strength-to-weight ratio and design flexibility . However, repeated and prolonged exposure to climatic and corrosive environments can progressively deteriorate composite structural interfaces, fastening regions, and weaken the structural integrity of flight-critical UAV subsystems . This study investigates the influence of environmental conditioning on three composite systems—carbon fiber/epoxy (CF/epoxy), glass fiber/epoxy (GF/epoxy), and glass fiber/polyester (GF/polyester)—using ISO 9227/ASTM B117 and MIL-STD-810H test procedures. Finite element analysis coupled with experiments revealed the degradation of composite fastening integrity under environmental conditioning.

2. Methodology

The degradation behavior of fiber-reinforced polymer composites was investigated through

a series of accelerated environmental conditioning designed to simulate harsh environmental conditions. Three composite material systems—CF/epoxy, GF/epoxy, and GF/polyester—were subjected to controlled corrosive and climatic exposures following internationally recognized testing standards. Corrosive degradation was evaluated using the Neutral Salt Spray (NSS) test conducted in accordance with ISO 9227/ASTM B117 standards. Specimens were exposed to a 5% NaCl solution in a salt spray chamber maintained at approximately 35 °C for 96 hours. Mass measurements were performed before exposure, immediately after the test, and following a 48-hour drying period to evaluate moisture uptake and salt deposition effects. Visual inspections were immediately conducted to identify surface changes or corrosion-related damage. Thermal aging effects were investigated through high- and low-temperature storage tests based on MIL-STD-810H environmental test procedures. High-temperature exposure was conducted following Method 501.6 to assess material behavior under elevated temperatures, including resin softening and thermal degradation. Low-temperature conditioning followed Method 502.6, where specimens were stored at −54 °C to evaluate embrittlement and microcrack formation caused by thermal contraction. Temperature and humidity profiles were monitored throughout the conditioning cycles. Aggravated temperature-humidity test was further conducted according to MIL-STD-810H Method 507.6. In this test, specimens were exposed to cyclic environmental conditions with relative humidity levels reaching 95% and controlled temperature variations designed to promote condensation and moisture absorption. These cyclic conditions simulate high-humidity service environments frequently encountered in coastal regions . Following environmental conditioning, tensile tests were conducted in accordance with ASTM D3039. Neat specimens were used as baseline controls to quantify tensile strength retention. Weibull analysis was employed to characterize variability in mechanical performance under environmental effects. Building upon previous studies on UAV performance , the present investigation contributes to the understanding of environmentally induced degradation effects on fastening reliability in flight-critical UAV composite structures.

3. Results / Conclusions

The experimental results showed that environmental exposure significantly affected both moisture absorption and tensile strength of the composite samples. In the NSS test, CF/epoxy exhibited the lowest weight gain after exposure (0.232%) and after drying (0.095%), demonstrating the best resistance to salt and moisture penetration. A similar trend was observed during storage low-temperature tests, where weight increases were 5.88% for CF/epoxy, 6.67% for GF/polyester, and 7.14% for GF/epoxy. Compared with the neat samples, aggravated temperature-humidity test caused a slight changes in samples of GF/polyester and GF/epoxy by 2.7% and 1.3%, respectively. Under strorage low-temperature conditions, tensile strength increased by 12.3% for CF/epoxy and 14.7% for GF/epoxy, whereas GF/polyester exhibited a 38.5% reduction. Combined experimental and finite element analysis results indicated that environmental conditioning progressively degrades the structural integrity and fastening reliability of FRP composite systems, while CF/epoxy exhibited superior environmental durability compared with GF-reinforced composites.

Dynamic Simulation of Split-Wheel Cold Air Unit for Aircraft Thermal Management

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1. Introduction

The aircraft environment is highly influenced by its speed and flying elevation . To monitor its cabin pressure and temperature with respect to its speed and elevation, the air cycle-based system is used, known as the environment control system (ECS) . It consists of several key components, including compact heat exchangers, a cold-air unit (CAU), valves, and other components, assembled into different ECS architectures. The CAU is the heart of ECS, consisting of a fan, a compressor, and a turbine connected by a mechanical shaft. A few studies have been carried out on the dynamic simulation of ECS facets in system-level analysis, and most focus on steady-state analysis, exergy analysis, and ECS optimisation. To address this research gap, this paper developed a dynamic model of a novel split-wheel cold air unit and evaluated its dynamic response.

2. Methodology

The dynamic model of the split-wheel CAU consists of a compressor and a cooling turbine connected by a mechanical shaft, and a separate fan and cooling turbine connected by a mechanical shaft, as illustrated in Figure 1. The model is built inside the ECS library of 1-D simulation commercial software Dymola®. The boundary conditions are defined using the pressure and temperature source/sink available in the ECS library.

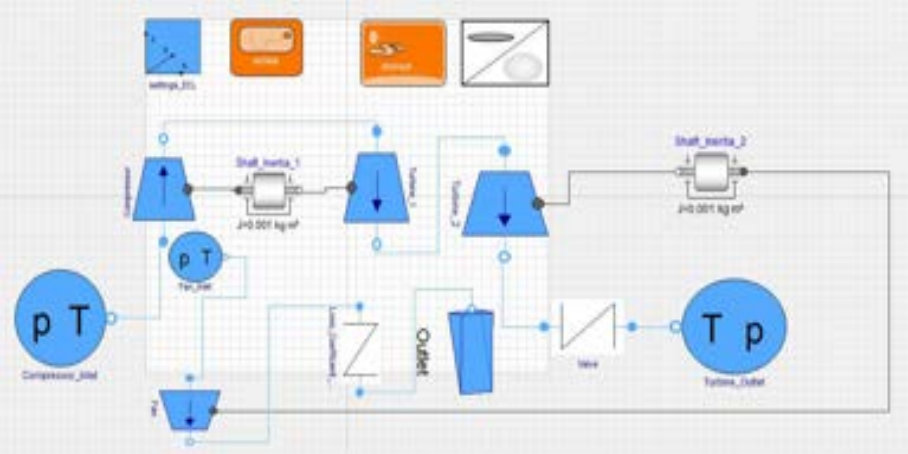


Figure 1. *Dynamic model of split-wheel CAU.*

3. Conclusions

In this paper, the influence of the shaft mass moment of inertia (MOI) on the dynamic response of a split-wheel CAU is analysed in terms of the exit temperatures of the compressor and the cooling turbine, as illustrated in Figure 2. The study concludes that the shaft MOI significantly affects the dynamic response of the split-wheel CAU, and it increases with an increase in shaft MOI. The dynamic response varies from around 25 to 85 s, with the shaft MOI

ranging from 0.001 to 0.009 kg.m². Additionally, the dynamic response is evaluated for corrected speed, corrected flow, shaft power, shaft torque and shaft speed. The developed dynamic model is useful for various aerospace applications related to aircraft thermal management. In the future, a system-level dynamic model of split-wheel ECS will be developed to estimate dynamic performance for real-time flight operations of civil aircraft, including the ground, take-off, cruise, and landing phases.

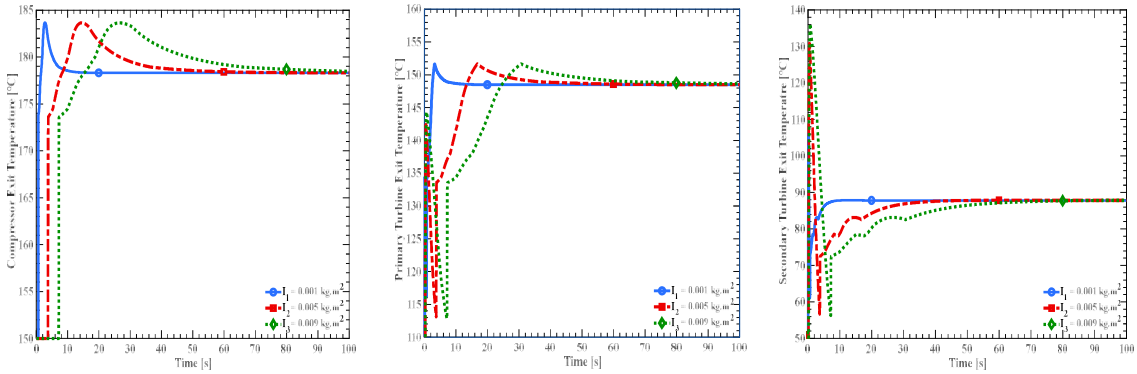


Figure 2. *Dynamic response of split-wheel CAU.*

LWC sensor for UAVs designed for operating in icing conditions

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1. Introduction

This study presents a liquid water content (LWC) sensor for unmanned aerial vehicles (UAVs) that is currently under development at the Łukasiewicz Research Network – Institute of Aviation as part of the SOPEL project (an anti-icing system), intended for operation in icing conditions.

The motivation behind this project was to extend the flight time of the UAV whilst using an anti-icing system; by utilising LWC data, the system does not need to operate at maximum power but can adjust its output according to flight conditions, leaving more energy available for the electric propulsion system. At the same time, the lack of such devices on the market, particularly in the required dimensions, led to the commencement of work on the LWC sensor.

2. Methodology

The methodology, which is based on measuring the difference in power consumption while maintaining a constant temperature between two measuring heaters (one of which is located directly in the air-water flow and the other of which is shielded from the water but not the airflow), will be demonstrated. Information on airflow velocity and temperature,

provided by other sensors, will also be utilised.
The mechanical design of the sensor, which comprises high-temperature resin and an aluminium profiled inlet, as well as aluminium heaters with copper heating tracks and an anti-icing protection method, will be presented. Furthermore, the implementation and execution of the measurement methodology method based on differential measurement of resistance and power using a 4-wire connection and analogue-to-digital conversion by the electronic circuit, a brief overview of software logic, the processing of measurement results, the test procedure, and the integration of data from auxiliary sensors will be shown.
The challenges and problems encountered in designing the sensor so far will also be presented, along with measures to address them and plans for further development, with a particular emphasis on improving the system's performance and reliability.
T To illustrate the current state of the design, a prototype version of the sensor is shown in Figure 1, which differs from the final version in that it has an extended cable shield (the vertical section of the sensor) and a different mounting arrangement to that used on the UAV, adapted for the test bench.

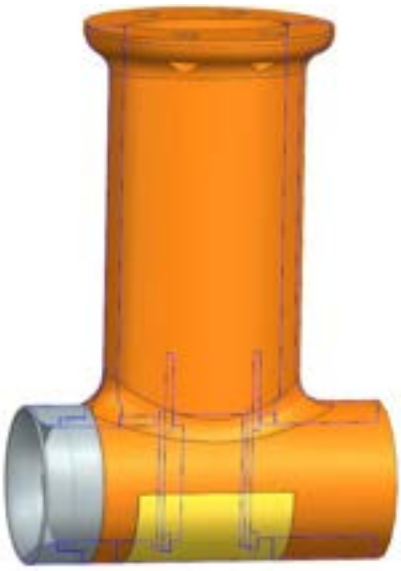


Figure 1. *A prototype test version of the LWC sensor.*

The mechanical design and assembly of the sensor were carried out using Siemens NX, the heaters and electronics were modelled in Altium Designer, and simulations of the inlet geometry with regard to icing, as well as air and water droplet flow, were performed using Ansys.

3. Conclusions

At the current stage of the project's development, the measurement method have been successfully validated, an accuracy of +/- 0.04 g/m³ for specific measurement points during tunnel tests has been achieved, prevented icing inside the sensor, and integrated temperature and flow velocity data into the software.
Further tests and project activities are planned between the abstract submission and the

conference, including increasing measurement accuracy, introducing automated data processing with calibration corrections, and implementing communication with other sensors and the UAV controller via CAN.
The positive results achieved so far and the considerable interest in LWC sensors for UAVs (several enquiries on this subject) indicate that there is a market demand for this type of sensor and suggest that this could be an interesting topic to present at the conference.

Simulation-Based Design of a Fuel Cell Electric Powertrain for a 10-Passenger Aircraft

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[2] Graz University of Technology, Austria

1. Introduction / Objectives

The decarbonisation of CS-23 aviation requires propulsion concepts that enable zero-emission operation while meeting strict constraints on mass, volume, safety, and certification. This work presents a model-based methodology for the development and optimisation of a fuel cell electric powertrain for a 10-passenger aircraft. The investigated architecture includes liquid hydrogen storage, fuel cell systems, a battery system, inverters, electric motors, and propellers. Based on aircraft-level requirements and certification-relevant boundary conditions, a generic flight mission is defined to derive power demands and transient load profiles. Coupled powertrain and longitudinal aircraft simulations are applied to assess flight performance, dynamic behaviour, hydrogen consumption, thermal-management loads, and propulsion efficiency. A value-based assessment is used to evaluate the trade-off between fuel cell system sizing and battery capacity with respect to powertrain mass, volume, and efficiency. The objective is to identify a feasible powertrain configuration and operating strategy for hydrogen-electric regional aviation.

2. Methodology

A coupled simulation and optimisation workflow was established to derive a feasible fuel cell electric powertrain architecture for the target 10-passenger aircraft. The workflow combines longitudinal aircraft simulation in AVL Cruise M with a quasi-stationary powertrain model implemented in Microsoft Excel, as shown in Figure 1. A generic CS-23 flight mission is translated into flight-phase-specific shaft-power requirements based on aircraft-level boundary conditions and literature data from comparable aircraft. This resulting power profile is then used as input for the powertrain model.
The quasi-stationary model evaluates different combinations of fuel cell system power and battery capacity. For each configuration, the minimum required battery capacity is determined while accounting for peak-power capability, battery C-rate limitations, and state-of-charge constraints. Fuel cell operation is parameterised by rated power, net efficiency, compressor pressure ratio, and altitude-dependent cathode supply conditions. Battery operation is described by usable capacity, power capability, C-rate limits, and the permitted state-of-charge window. Component masses and volumes are estimated using

implemented values for specific power, specific energy, and specific volume. The resulting outputs include hydrogen consumption, thermal-management loads, propulsion efficiency, and the mass and volume contributions of the liquid hydrogen storage system, fuel cell system, battery, inverters, electric motors, and thermal-management systems. In parallel, literature-based technology trend analyses are used to assess current challenges and opportunities beyond 2035. A value-based assessment is applied to identify the optimum trade-off between fuel cell system sizing and battery capacity with respect to powertrain mass, volume, and efficiency.



Figure 1. *Simulation methodology of the fuel cell electric powertrain*

The selected configuration is then transferred to the longitudinal aircraft simulation to investigate climb capability, transient power demand, and mission fulfilment, taking into account C-rate limitations of the battery in the dynamic response capability of the aircraft. Fuel cell stack behaviour is represented by polarisation curves, while system power is scaled through suitable series and parallel stack arrangements. The time-resolved shaft-power demand obtained from the longitudinal simulation is fed back into the powertrain model, enabling iterative refinement of component sizing and operating strategy.

3. Results / Conclusions

The simulation results indicate relevant design trends for the sizing and operation of a fuel cell electric CS-23 powertrain. The investigated configurations show that a purely battery-electric architecture is not suitable for the targeted aircraft class, while a fuel cell dominant hybrid concept offers a more promising solution by combining sustained fuel cell operation with

battery-based transient power support. A key trade-off was identified between fuel cell system size, take-off power capability, cooling demand, and overall powertrain mass. In particular, take-off represents a critical operating point, as high propulsion power coincides with elevated outside temperatures, resulting in peak thermal-management loads. Oversizing the fuel cell system can reduce battery support requirements but increases system mass, volume, and cooling effort. The simulations further show the influence of compressor pressure ratio, cruise speed, and power-split strategy on hydrogen consumption, efficiency, and range, supporting the identification of promising design windows for further development.

Liquid Hydrogen Supply for the BALIS Test Environment

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1. Introduction / Objectives

Reducing the carbon footprint of air transport while maintaining the current global mobility is the overarching goal of clean and sustainable aviation and a major challenge for the decarbonization of the transport sector. Enhancing the degree of electrification of the main propulsion system is seen as one approach to increase efficiency and reduce pollutant emissions of regional aircraft.
The aim of the DLR BALIS test infrastructure is the experimental investigation of such powertrain systems based on a fuel cell systems in the megawatt scale on ground . The preferred energy carrier for electric propulsion in aviation is liquid hydrogen (LH2) due to its higher density compared to high pressure gas storage . This paper presents an overview of the BALIS liquid hydrogen supply system, test capabilities and the current status.

2. Methodology

The liquid hydrogen infrastructure of the BALIS test site is currently in its design phase and will be commissioned by end of 2026. The liquid hydrogen system is designed to provide safe and reliable hydrogen supply to the 1.5 MW fuel cell test field. It consists of the basic BALIS LH2 infrastructure and the BALIS LH2 test field. The LH2 test field houses the liquid hydrogen storage and conditioning unit under test. It features a realistic, aviation-relevant test tank with a storage capacity of 200 kg LH2 and a water/glycol heated evaporator (EGW).
The BALIS LH2 infrastructure stores and distributes the liquid hydrogen of the test site. The core component is a 60 m^3 storage tank containing 3.8 metric tons of liquid hydrogen. Two dedicated discharge lines deliver liquid hydrogen either to the test tank in the LH2 test field or to feed the fuel cells directly. Since the LH2 test field is a research unit, it will undergo downtimes for maintenance, upgrades or debugging. Therefore, the second path ensures the hydrogen supply for the fuel cell test field and relies on non-aviation grade standard components such as an air evaporator and a trim heater. The overall process flow diagram is illustrated in Figure 1.

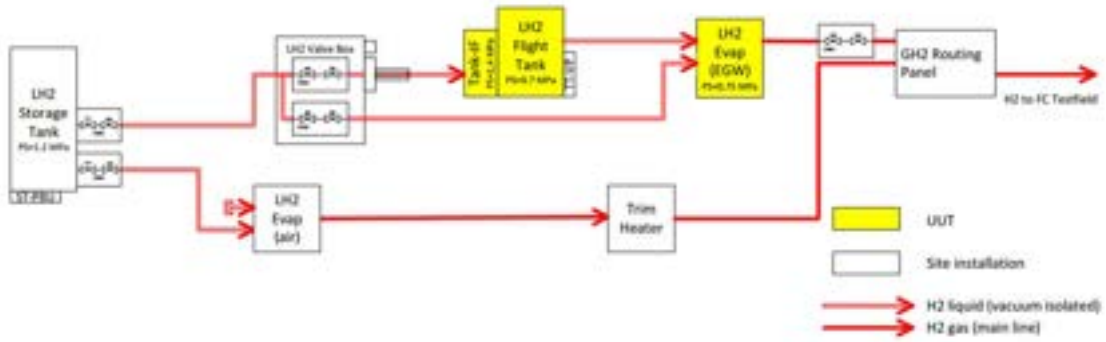


Figure 1. *Illustration of the architecture of the LH2 supply system for the BALIS test environment. The yellow boxes resemble the LH2 test field with the units under test 'LH2 flight tank' and 'LH2 Evaporator (EGW)'.*

3. Results / Conclusions

The BALIS LH2 system is designed to investigate the behavior of the liquid hydrogen supply and conditioning system under aviation-relevant conditions. Alternating high and low power phases such as taxi to take-off and cruise flight, but also external or internal failure injections such as loss of fuel cell or vaporizer power will be tested. At the time of the conference, the system will be in its final installation and commissioning phase. The paper will present the setup of the LH2 system in detail, elaborate on its capabilities, the current status of the installation and commissioning and will give an outlook on the further planned scientific use-cases.

Enhancing Reliability Analysis to Improve Maintenance Decisions

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Amsterdam University of Applied Sciences, The Netherlands

1. Introduction / Objectives

Aircraft maintenance planning increasingly exceeds the capabilities of traditional metrics such as Mean Time Between Failures (MTBF), which rely on static historical averages and overlook real degradation dynamics. As Hall & Strutt noted in , such time-based strategies are no longer adequate for complex failure behaviours, often leading to premature or delayed replacements that elevate operational costs and AOG exposure. The consequences are substantial: EUROCONTROL estimates delays cost European carriers €45–100 per minute , while workforce shortages further constrain maintenance flexibility. Although data-driven reliability methods have advanced, many models still depend on simplified assumptions that fail to capture operational variability, leaving maintenance largely

diagnostic rather than prognostic . FAA guidance similarly emphasizes the need for continuous data analysis beyond static MTBF metrics . This study addresses these limitations by introducing survival-analysis-based reliability models that incorporate repair cycles, component modifications, and serial-number-level histories to improve failure forecasting and support proactive maintenance planning.

2. Methodology

This study examines the impact of historical maintenance records, specifically the number and timing of repairs and modifications, on reliability modeling and the prediction of remaining useful life. The study began with extensive real-world data integration, resulting in a dataset of 1,187 observations across 703 unique serial numbers spanning 2016 to 2024 created by consolidating repair and modification records. To improve Remaining Useful Life (RUL) forecasting, four advanced survival analysis models were evaluated: the Cox Proportional Hazards (CPH) model to account for repeated observations per serial number, the Restricted Cubic Spline CPH to capture non-linear effects and correct proportional hazard violations, the Cox PH with Time-Varying Covariates (CTV) to model evolving risks from cumulative repairs and the Weibull Accelerated Failure Time (AFT) model to assess covariate time-scaling effects. These models resulted in a simulation framework that combined CPH cubic splines with 1,000-draw Monte Carlo simulations, enabling the generation of precise, component-specific RUL distributions for censored, in-service parts.

3. Results / Conclusions

The results show that integrating serial-number tracking, cumulative repair history, and modification status significantly improves failure forecasting for Cabin Air Compressors. Consistent with findings from and , this study confirms that repair frequency strongly increases hazard rates and reduces remaining useful life. Recurrent-event survival models outperformed traditional approaches, with spline-enhanced and time-varying Cox models achieving superior fit. The CTV model delivered the best performance (AIC 10,095.19; C-index 0.58), improving substantially over the baseline model. Monte Carlo simulations produced individualized RUL distributions, revealing concentrated end-of-life periods—especially for components with multiple repairs—and enabling clearer risk classification. Median RUL declined from roughly 1,080 days (0 repairs) to 410 days (3+ repairs), demonstrating that repaired units do not return to “as-new” reliability. Overall, the study validates the operational value of advanced survival analysis for proactive maintenance and spare-parts planning. visually reinforces this limitation: survival curves for components with four and five repairs appear artificially higher than those with three repairs, contradicting expected degradation patterns. This anomaly aligns with the low sample sizes in these upper repair categories, indicating that the apparent reliability increase is a data-sparsity artefact rather than a true operational effect. Figure1 shows a sample of results for the CPH frailty with splines partial effects.

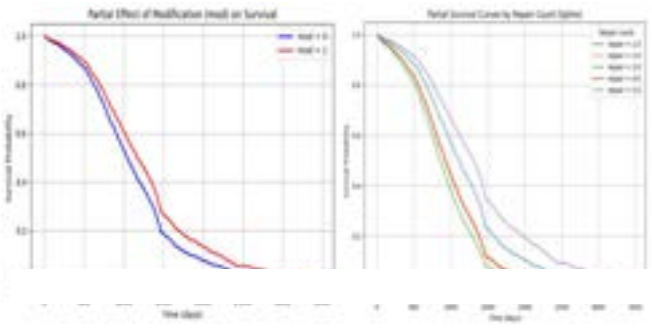


Figure 1. *CPH Frailty with Splines Partial Effects (x label, days, I removed due to confidentiality issues).*

Variable Rotor Speed Transmission Architecture for Energy-Efficient Operation Across Multiple Flight Conditions in High-Speed Vertical Lift Aircraft

Helmut Mad, Jonas Koch
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1. Introduction / Objectives

Future high-speed vertical lift platforms such as the Airbus RACER demonstrator and next-generation tiltrotor concept of Leonardo require transmission architectures capable of reconciling hover efficiency, cruise performance, acoustic emission reduction, and fuel economy. Conventional fixed-ratio rotorcraft transmissions force the rotor system to operate at a compromise design point across the complete flight envelope, limiting aerodynamic efficiency and mission adaptability. Recent research on Variable Rotor Speed concepts has shown that adaptive rotor speed control can reduce emissions while enabling power savings up to 20% depending on blade loading and advance ratio.
This work investigates the applicability of continuously variable compound-split transmission architectures with electric variators for future vertical lift applications. Particular focus is placed on variable rotor speed as a promising energy-efficient approach for achieving optimum rotor operating conditions across different mission phases. The presented methodology combines drivetrain design, dynamic simulation, and pilot-in-the-loop evaluation within a representative rotorcraft simulation environment.

2. Methodology

The investigated drivetrain concept is based on a compound-split transmission architecture integrating two coupled planetary gear stages and electric variator units arranged in a motor-generator loop. The architecture enables continuous adaptation of rotor speed while maintaining the turboshaft engine close to its optimal operating point, thereby maximizing overall propulsion efficiency.
The drivetrain topology was developed within the VARI-SPEED-II research framework using FVA-Workbench-supported gearbox synthesis and system-level dynamic simulation. Unlike

conventional gearbox concepts with fixed transmission ratios, the proposed compound-split arrangement routes only a limited portion of the transmitted power through the electrical variator path, while the majority of the power flow remains mechanical. This configuration combines the efficiency benefits of conventional rotorcraft transmissions with the flexibility of electrically assisted rotor speed adaptation.
A real-time capable drivetrain model was coupled with a UH-60-class rotorcraft flight dynamics simulation implemented in the ARCS rotorcraft simulation framework. The integrated simulation environment included a GE T700-class turboshaft engine model, blade-element-based rotor aerodynamics, Pitt-Peters dynamic inflow modeling, and a comprehensive variable-speed transmission model translated from MATLAB/Simulink into C++ for pilot-in-the-loop operation.
The methodology further incorporated operational evaluations within the ROSIEX helicopter simulator environment at the Technical University of Munich. Standardized ADS-33E-PRF Mission Task Elements, including stabilized cruise, climb and descent maneuvers, standard-rate turns, and dynamic rotor-speed transitions, were performed under varying rotor speed conditions ranging from 73.3% to 110% of nominal rotor speed.
To minimize trim disturbances during rotor-speed transitions, an open-loop collective compensation controller was implemented using precomputed lookup tables derived from aerodynamic simulations.
The controller adjusted collective pitch through a feedforward input based on advance ratio, blade loading, and instantaneous rotor speed.
System assessment combined objective drivetrain and flight-dynamics measurements with subjective pilot evaluations based on Cooper-Harper Handling Qualities Ratings and Bedford Workload Ratings. Particular attention was given to transient drivetrain behavior, controllability during dynamic rotor-speed adaptation, and the operational feasibility of continuously variable rotor-speed management for future high-speed vertical-lift applications.

3. Results / Conclusions

The investigations demonstrated that continuously variable rotor-speed transitions of up to 20% can be achieved. Operational simulations further demonstrated fuel and power savings of up to 5% during reduced rotor-speed cruise operation while maintaining acceptable handling qualities.
The results indicate that compound-split transmissions with electric variators represent a promising enabling technology for future high-speed vertical-lift aircraft such as the Airbus RACER demonstrator and next-generation tiltrotor concepts of Leonardo. Variable rotor-speed operation appears to be one of the most energy-efficient approaches for maintaining optimal rotor aerodynamic performance across the flight envelope.

From an airworthiness and certification perspective, UAV platforms provide a significantly more suitable environment for early technology maturation than manned rotorcraft. Reduced certification complexity, lower operational risk, and faster experimental approval cycles enable accelerated validation of adaptive propulsion and transmission systems. The FEVARI research program at TUM therefore represents an important intermediate step towards future certificated high-speed vertical-lift applications.



Figure 1. *Variable ratio helicopter-main-transmission model used for feasibility studies*

From Airspace Efficiency to Acceptance: Towards a Social Impact KPA for U-space

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Future Needs Management Consulting Ltd, Cyprus

1. Introduction / Objectives

The growing use of Unmanned Aircraft Systems (UAS) and U-space in cities is shifting drones from aviation tools to key parts of urban mobility, intensifying societal impacts like noise, safety perception, and public acceptance. Current U-space performance frameworks, such as the PJ19 U-space Performance Framework - U-space Companion Document, focus heavily on technical and operational efficiency, leaving social and urban concerns fragmented. This study proposes using Sustainable Urban Mobility Indicators (SUMI/SUAMI) to complement socially relevant PJ19 Key Performance Indicators (KPIs). The goal is to develop a social-performance perspective for U-space assessment through a cross-framework alignment, identifying urban sustainability indicators that enhance the societal evaluation of U-space operations. The proposed approach could support policymakers, municipalities and U-space service providers in integrating societal considerations into future urban drone governance.

2. Methodology

The methodology of this study is based on a cross-framework alignment approach aimed at extending the social assessment capabilities of the PJ19 U-space Performance Framework - U-space Companion Document. PJ19 was selected as the operational baseline because it provides a structured and aviation-oriented framework for evaluating U-space performance through Key Performance Areas (KPAs) and Key Performance Indicators (KPIs). The analysis focused specifically on KPIs considered socially relevant, including indicators associated with Safety (SAF), Environment (ENV), Security (SEC), Access and Equity (A&E), Human Performance (HP), and Capacity (CAP). These indicators were selected because they directly or indirectly influence citizens, urban environments, and societal acceptance of drone operations. Selected PJ19 indicators were systematically mapped against Sustainable Urban Mobility Indicators (SUMI/SUAMI) to identify conceptual and measurable relationships

between operational U-space performance and broader urban sustainability objectives. To ensure consistency throughout the analysis, the relationships between indicators were classified into two categories. Direct alignment refers to indicators evaluating the same or highly comparable phenomena using similar measurement logic or units. Complementary alignment refers to indicators that are conceptually related and contribute to the assessment of broader societal impacts without measuring the same phenomenon.
The inclusion of SUMI/SUAMI indicators is motivated by the increasing integration of drone operations within urban mobility ecosystems. U-space services are expected to influence dimensions already commonly assessed in urban transport systems, including accessibility, congestion, environmental quality, public-space quality, and perceived safety. Consequently, urban mobility sustainability indicators provide an important societal and urban perspective that is currently not fully represented within operational U-space assessment frameworks.
The analysis was conducted through a qualitative and conceptual alignment process, where socially relevant pairings between PJ19 and SUMI/SUAMI indicators were identified and evaluated according to their operational relevance, urban relevance, and societal relevance. The resulting mappings were grouped into thematic categories, including safety, noise exposure, visual pollution, emissions, congestion, and security, enabling a structured interpretation of how urban sustainability indicators can support socially-aware U-space assessment (see also Fig.1).



Figure 1. *Methodology*

3. Results / Conclusions

The results revealed that the majority of relationships between PJ19 and SUMI/SUAMI indicators are complementary rather than direct. Only one direct alignment was identified between the PJ19 indicator "Actual Average CO_2 Emission per Flight" (U.ENV1) and the SUMI Greenhouse Gas Emissions indicator, as both evaluate comparable environmental-performance phenomena. Safety-related PJ19 KPIs were found to complement SUMI/SUAMI traffic-safety indicators, while PJ19 noise exposure indicators aligned conceptually with SUMI/SUAMI noise-hindrance metrics. Similarly, PJ19 visual exposure indicators complemented SUMI/SUAMI indicators related to public-space quality and urban liveability. The findings demonstrate that PJ12 KPIs alone are insufficient for comprehensively assessing the societal impacts of drone operations in urban environments. SUMI/SUAMI indicators contribute an urban sustainability perspective that is currently missing. Consequently, the

proposed cross-framework mapping represents a first step toward the development of a dedicated Social Impact Key Performance Area (KPA) for U-space operations.

A Multi-Stage Gearbox for Plug-In Hybrid Aircraft Propulsion with Unrestricted Turbine Airflow

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1. Introduction / Objectives

The EXACT Project aims to develop a Plug-In-Hybrid 250-Seat Short-Range Aircraft featuring a battery-electric drivetrain coupled with a gas turbine as a range extender . Each engine pod integrates a gas turbine, multiple electric motors/generators and a propeller, all coupled via a gearbox to allow each component to run at its optimal speed.
Conventional layouts require an S-duct inlet to route airflow around the gearbox, introducing aerodynamic penalties like non-uniform pressure distribution and flow separation which directly reduce turbine efficiency . This work proposes a novel layout in which the gearing is positioned around the turbine, enabling unrestricted direct axial airflow into the turbine and eliminating the S-duct entirely. The primary engineering challenges are the first reduction gear stage and the freewheel required between the turbine and the first reduction stage, both operating at extremely high speeds due to their direct coupling with the turbine.

2. Methodology

A CAD model of the proposed transmission was developed based on the layout shown in Figure1. The central aerodynamic advantage of the design is that the gearbox is positioned radially outside the turbine inlet annulus, leaving the axial flow path into the turbine completely unobstructed. By design this eliminates the need for an S-duct. A freewheel is positioned directly between the turbine output shaft and the first reduction stage, operating at full turbine speed. It decouples the turbine during all-electric operation, preventing the electric motors from back-driving the turbine and allowing the propeller to be driven independently. The freewheel represents a significant design challenge in parallel with the first gear stage, as both components must operate reliably at pitch-line and surface velocities far beyond conventional design practice.
The transmission architecture features three gear stages: a first reduction stage (i_1) steps down from the high-speed turbine shaft ($n_1 = n_t$) to an intermediate shaft (n_2). This intermediate shaft carries two pinion gears. The first connects to two electric motors/generators running at $n_3 = n_m$, they are offset angularly via stage i_2. The second pinion gear provides a further reduction via stage i_3 to $n_4 = n_p$, matching the optimal propeller speed. Gear geometry and load-carrying capacity were calculated using FVA Workbench in accordance with ISO 6336, which covers tooth root and flank strength. Special attention was given to material selection, lubrication strategy, and bearing arrangement for the first stage due to the extreme pitch-line velocities encountered.

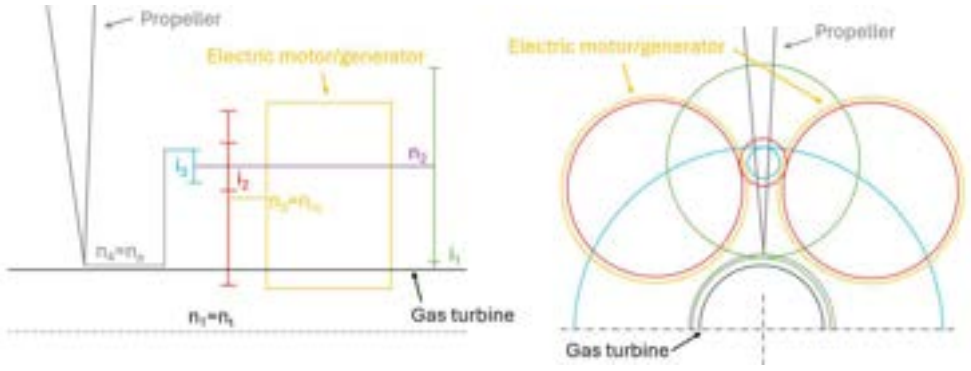


Figure 1. Layout of the transmission.

3. Results / Conclusions

The analysis demonstrates that a compact, multi-stage gearbox incorporating a freewheel at the turbine interface can be designed to achieve high transmission efficiency while accommodating the demanding speed differential between the gas turbine, electric motors/generators, and propeller.

Critically, by positioning the gearing externally and eliminating the S-duct, the design avoids the losses inherent to conventional inlet geometries. This yields a measurable gain in cycle efficiency and specific fuel consumption of the turbine. The combination of improved inlet conditions and a high-efficiency multi-stage gearbox confirms the potential of this architecture to outperform conventional layouts on overall propulsive efficiency. The freewheel and first gear stage nonetheless remain the most critical components requiring further detailed analysis and experimental validation at the extreme operating speeds involved.

A Methodical Simulation of Cost-Constrained Decarbonization Pathways for the Air Transport System

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1. Introduction / Objectives

Global warming forces aviation to target net-zero emissions by 2050. Conventional incremental gains are insufficient, and potential solutions such as shifting to SAF or hydrogen demand systemic operational transformation. This aligns with EASN's "Clean Aviation Moonshot" for frameworks integrating operational efficiency and economic viability.

Modeling these complex system changes requires advanced tools. Unlike macro-scale or simplified models (World3, AIM, Aeromaps) that lack tactical fidelity, this study introduces an innovative and refined operational simulation framework. Backed by the French Official Services' scientific roadmap and answering EASN's call for evidence-based strategic tools, our multi-commodity flow approach bridges macroeconomic assumptions and routing

realities. By optimizing network topologies, this paper evaluates dynamic yearly transition pathways, providing refined decision-support metrics for air transport decarbonization.

2. Methodology

To formulate the multi-period structural evolution of airline networks, the optimization problem is modeled as a multi-commodity flow network. Let a complete network configuration be defined as $x = (f, a) \in \mathcal{X}$, where f represents the operational flight schedule, a denotes the multi-fleet type allocation, and $\mathcal{X}$ is the set of admissible configurations satisfying multi-commodity demand constraints. The baseline objective function $Z(x)$ evaluates the system-wide carbon emissions. Setting the decarbonization horizons for 2050 starting from 2026, the long-term pathway is modeled through a sequence of 24 yearly iterations, where one distinct air transport network is optimized sequentially per year. The single-period transition from a state x_n to the subsequent year x_{n+1} is constrained by an annual step-length tolerance $\delta_n > 0$:

$$\forall n = 0,1,\dots,23: x_{n+1} \in \arg\min_{x \in \mathcal{X}} Z(x) \quad \text{subject to} \quad c(x_n, x) \leq \delta_n$$

Where $c(x_n, x)$ represents the generalized transition cost function regulating state modifications.

To investigate this solution sequence under concrete numerical scenarios, we consider a simplified foundational case where the step-by-step transition cost function is explicitly represented by the following multi-commodity network variation cost expression, denoted as $D(A, B)$ between two state configurations:

$$c(A, B) \triangleq D(A, B) = \sum_{s \in AP} \sum_{t \in AP} \sum_{m \in AC} \sum_{(o,d) \in OD} \alpha_{s,t,m} \cdot \left| x_{s,t,m}^{o,d}(A) - x_{s,t,m}^{o,d}(B) \right|$$

Where AP, AC, and OD represent the universal sets of airports, aircraft types, and origin-destination pairs, respectively, while $x_{s,t,m}^{o,d}$ denotes the continuous passenger payload allocated on segment (s, t).

Crucially, while this function serves mathematically as the active localized constraint within each annual optimization step, it also possesses rigorous geometric properties. Post-simulation, this same expression can be comprehensively utilized as a network distance metric. By tracking the geometric displacement between any iterative state x_n and the unconstrained theoretical optimum x_{opt}, this dual-purpose proxy provides the exact diagnostic telemetry required to assess the asymptotic convergence behavior and alternative optima profiles investigated in the subsequent sections.

3. Results / Conclusions

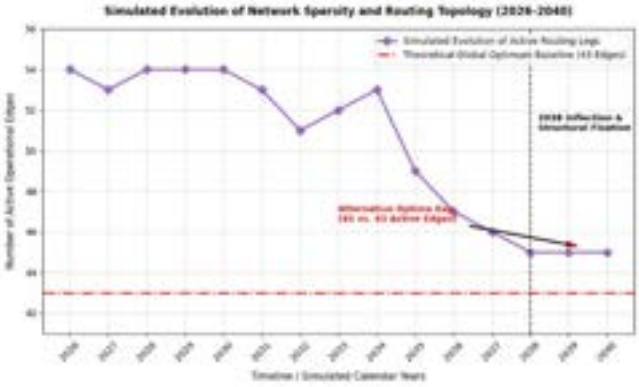


Figure 1. Network sparsity timeline

This study uncovers the structural evolution laws of airline networks across a four-country European network (FR, UK, ES, PT) and a high-density French domestic network. Evaluated via a multi-commodity distance metric, the macro-scale European network successfully achieves asymptotic convergence toward the global optimum. Conversely, as illustrated in the network sparsity timeline[Figure 1], the dense French network maintains a linear fleet substitution path until reaching a decisive structural inflection in 2038, failing to fully converge to the theoretical baseline. Instead, the trajectory reaches a stable plateau from 2038 to 2040, mathematically demonstrating *alternative optima* (45 vs. 43 active operational edges) on the identical carbon-optimal frontier. These findings prove that network evolutionary behavior is highly scenario-dependent. The potential impact of this research is critical for airspace management, proving that routing density must be explicitly integrated into environmental policies to accurately predict long-term system optimization trajectories.

Optimized Cockpit structure manufactured via explosive forming

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1. Introduction / Objectives

To meet aerospace demands for weight and cost reduction, this study proposes an optimized cockpit structure manufactured via explosive forming (explo-forming). Traditional methods suffer from high assembly costs and weight penalties. To overcome these limitations, this work introduces a technological innovation focusing on the deep-drawing of exceptionally large and thick double-curvature sheet metals into a single integral blank. This approach maximizes functional integration and minimizes residual stresses. Ultimately, this research delivers a novel manufacturing model for next-generation cockpits, balancing high structural performance with economic viability.

2. Methodology

The methodology integrates geometric design, manufacturing constraints, and advanced numerical simulations. First, a master geometry is defined based on explo-forming capabilities. To comply with process dimensional limits, an initial structural breakdown

partitions the cockpit into optimized sub-sections. The manufacturing feasibility of these large-scale components is then evaluated using numerical forming simulations to assess material flow and formability limits. Once validated, a comprehensive Digital Mock-Up (DMU) of the integrated structure is generated. Finally, structural integrity and airworthiness are verified through finite element analysis (FEA), including static stress analysis and high-velocity bird strike simulations to ensure compliance with aerospace safety standards.

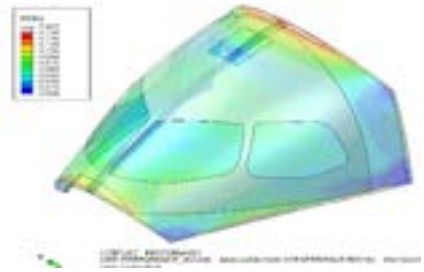


Figure 1. *Integral Explo-forming simulation*



Figure 2. *Three integral part prelim design*

3. Results / Conclusions

Results indicate that the cockpit must be partitioned into three integral blanks, requiring minor aerodynamic profile adaptations. Numerical analyses reveal that structural stiffness is a primary challenge, as thickness limitations restrict structural inertia. Furthermore, post-forming machining of these large components emerges as a critical technical hurdle. Despite these constraints, the integrated design drastically reduces part count and assembly complexity. Future steps will evaluate the aerodynamic impact of the geometric modifications, perform fatigue and crack propagation sizing, and conduct a detailed weight and economic assessment to fully quantify the cost-effectiveness of this manufacturing route.

A Cross-Domain Approach to Space System Requirements Engineering: Integrating ECSS with Selected ARP4754 Practices

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1. Introduction / Objectives

Space projects require a disciplined approach to translating mission needs and stakeholder expectations into verifiable technical requirements, as supported by the ECSS system engineering and technical requirements specification standards. However, in many projects, the transition from operational goals to stable functional and requirement baselines remains highly dependent on local engineering practices, which can reduce repeatability and traceability across system levels. Although the ARP4754A standard provides a robust framework for system development and requirement validation, the integration of this standard into ECSS-driven requirements elicitation workflows for space systems remains insufficiently addressed.

This work proposes a technical method for requirements elicitation and functional

decomposition under ECSS, enhanced with selected practices derived from ARP4754A, and applies this method to the Engine Control Unit ECU and CubeSat platform (SPARK) to evaluate its repeatability, engineering value and suitability for different space system configurations.

2. Methodology

The proposed approach is organised as a staged engineering workflow aligned with the technical requirements specification logic of ECSS system engineering requirements. It incorporates practices inspired by ARP4754A for functional analysis, top-down allocation, requirement validation, and development-oriented decomposition. The structured representation and consistency of system engineering artefacts is supported by selected MBSE elements.

The method involves creating an intermediate artefact layer comprising a mission-to-capabilities mapping, a function-to-requirement allocation matrix and a preliminary verification allocation table that links each requirement to its intended verification.

This approach was evaluated using two complementary case studies, which reflect different system engineering scopes. SPARK is a CubeSat space system in which the process is applied at full system level to structure mission-driven functional architecture and derive a coherent requirements baseline. In this case, selected ARP4754A practices are used to support the definition of system-level functions, allocation of functions to subsystems (e.g. power, ADCS, communication, payload. On the other hand, the Engine Control Unit (ECU) represents a component developed as part of a larger space platform, providing a more detailed view on lower-level system decomposition. The ARP4754A-inspired approach is applied in this case down to the item level, enabling the subsystem to be broken down into its constituent elements and interfaces in a structured way. This detailed decomposition supports the explicit derivation of requirements at multiple levels while maintaining visibility of key system functions and top-level constraints. It also facilitates clearer mapping between architecture, allocated responsibilities and verification activities, improving the handling of safety-relevant aspects through the more systematic identification of critical elements and their interactions.

For both systems, the same sequence is executed: stakeholder expectation capture, operational scenario definition, functional decomposition, requirement derivation, allocation, traceability establishment, and preliminary verification mapping.

3. Results / Conclusions

It has been demonstrated that this extended approach provides better functional coverage and fewer gaps, as well as being more verifiable. While there are studies comparing aviation and space standards and discussing cross-domain assurance, there are fewer publications that implement this as a specific process for creating space system requirements under ECSS, incorporating certain ARP4754 practices in a controlled manner.

The application of the proposed method enabled the development of consistent functional, physical, and logical architectures for both case studies This method enabled the identification of features that were initially concealed and their incorporation into the architectures. Alongside the architectures, sets of requirements at several levels were drawn up and both internal and external interfaces were precisely identified and defined. Hardware and software design have been translated directly as a result. All artefacts can be

made controllable, consistent and traceable. Integration happens automatically. As work is carried out on each identified component, everything falls into place and a coherent system emerges.

Evaluation of bending ductility and fracture surface analysis in two additively manufactured complex cellular structures made of aluminum alloy

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1. Introduction

Cellular metamaterials offer direct benefits for components such as reduced weight, material efficiency and improved physical properties . They also provide secondary benefits in practical applications not only in the aerospace and automotive sectors, contributing to fuel savings and environmental protection, but also in biomedicine, healthcare or common household use. However, complex shapes of structures can currently only be fabricated using an additive approach, which still poses many challenges.
This study deals with a complex cellular structure, namely the Fischer-Koch S and Schoen IWP structures, implemented in a beam-type specimen with five different volume fractions.

2. Methodology

The bending properties of porous samples up to failure were experimentally determined at room temperature on a Zwick/Roell 1456 universal testing machine according to ISO 7438:2020 standard . For preliminary evaluation, two samples with the smallest and largest investigated volume fraction (10 and 35 %) were fabricated and heat-treated to remove internal stresses by 3D printing. These two samples were subjected to fractographic and EDX analysis using a Vega 3 Tescan electron microscope and a Brucker analyzer equipped with Esprit 19 software. The results showed the potential for improving properties by changing the input parameters and by heat treatment in two stages (artificial aging followed by solution annealing and aging) , to which the newly manufactured samples with all five investigated volume fractions were subjected. Three topologically identical specimens with the same volume fraction were fabricated from AlSi10Mg by SLM to verify the reproducibility of the results from a statistical point of view, so a total of 15 specimens were fabricated and subjected to bending testing. The crack propagation mode was evaluated from a macroscopic point of view for individual volume fractions, with the results being correlated with the ductility index and wall thickness of the structures.

3. Results

The results showed better properties of Fischer-Koch S structure in the whole investigated range of volume fractions and a large degree of topology influence on the crack propagation method. Figure 1 shows an example of damaged Fischer-Koch S sample with crack propagation.
Analysis of fracture surfaces showed that the wide range of powder particle diameters resulted in some small particles being burned and some not melted, indicating improperly set

input manufacturing parameters and conditions. The regions between the unmelted powder particles caused structural heterogeneity , while the incoherent or semi-coherent bonding of the unmelted particles to the matrix reduced the resistance to crack initiation and propagation. The particles/pores arranged in a line essentially located in the center of the cell wall (see Fig. 2) caused local cracks to form when the material sample was loaded, which propagated in the bridge (material between the individual cavities) perpendicular to the direction of loading of the sample.

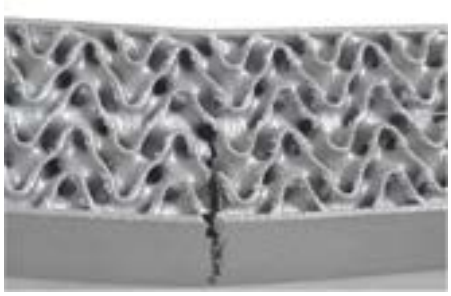


Figure 1. *Damaged Fischer-Koch S specimen after bending test with demonstration of crack propagation.*

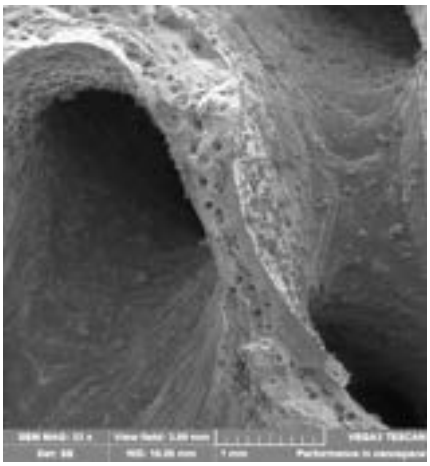


Figure 2. *The pores arranged in a line essentially located in the center of the cell wall.*

Experimental Analysis of GH2 Dispersion in Aircraft Cabin

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1. Introduction / Objectives

Aviation contributes significantly to global CO2 emissions, while decarbonization remains challenging due to continued growth in air travel demand . Using Hydrogen as an energy carrier is widely regarded as a promising long-term alternative to conventional kerosene-based propulsion, although its technological readiness level remains low. This is partly due to hydrogen's low density, high diffusivity, and flammability, which introduce substantial storage and safety challenges . To support the safe integration of hydrogen technologies in passenger aircraft, this study investigates leakage hydrogen gas (GH2) dispersion in a scaled aircraft cabin environment using helium as a surrogate. Flow visualization is performed using the background-oriented schlieren (BOS) technique . Experimental data on gas dispersion within the complex airflow conditions of passenger aircraft cabins remain limited, and this work aims to address this gap.

2. Methodology

Experiments are conducted in a geometrically scaled (1:16) section of an Airbus A320 cabin designed to replicate typical air distribution characteristics. The model is capable of integrating both conventional and newly proposed ventilation concepts, following the configurations investigated by Zhang et al. shown in Figure 1 . These flow patterns are qualitatively verified using smoke visualization.

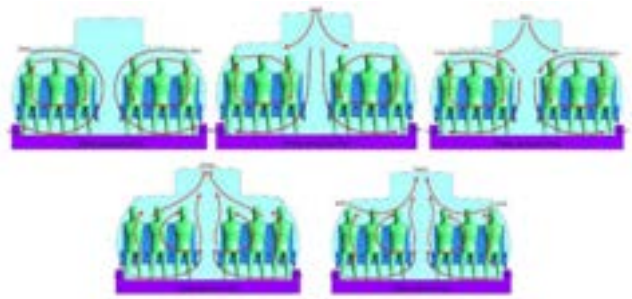


Figure 1. *Common and proposed Ventilation Principles by Zhang et. al. .*



Figure 2. *Test Cabin*
Segment CAD Model.

To enable the application of background-oriented schlieren (BOS), the scaling is implemented while maintaining optical accessibility and approximating dynamic similarity to the airflow conditions of the full-scale cabin. The experimental section depicted in Figure 2 comprises two modular seat rows and is fabricated using fused deposition modeling. The enclosure is sealed at both ends with transparent acrylic panels and rubber gaskets, ensuring sufficient airtightness while allowing transparency to a patterned background for BOS. The modular design enables variation of ventilation strategies, seating configurations, and leakage scenarios, facilitating systematic investigation of their influence on gas dispersion. Test scenarios include varying leak rates and release locations, such as the cabin floor, air supply ducts, and areas around overhead compartments. Although the scaled model does not preserve full dynamic similarity with a full-scale cabin, it captures key qualitative features of buoyancy-driven gas dispersion. Therefore, the observed helium behavior provides insight into general dispersion trends relevant to hydrogen in aircraft cabin environments. Helium is introduced into the cabin as a surrogate for hydrogen leakage due to its low density and

high diffusivity, which result in comparable dispersion behavior . Additionally, its refractive index difference relative to air enables non-intrusive visualization using BOS , . To validate the qualitative BOS results, complementary measurements are performed using hydrogen concentration sensors integrated into the enclosure. For this purpose, hydrogen is produced at low and therefore safe concentrations using a polymer electrolyte membrane reversible fuel cell. The resulting sensor data provide a quantitative reference for the dispersion behavior observed in the helium-based BOS experiments.

3. Results / Conclusions

Experimental investigations and data analysis are ongoing, and final results have not yet been obtained. The study focuses on identifying regions prone to gas accumulation, which may represent hazard zones in the event of a hydrogen leak. Preliminary validation is conducted using hydrogen concentration sensors, with low-concentration hydrogen releases providing a quantitative reference for the dispersion patterns observed in the helium-based BOS measurements. This approach enables assessment of the consistency between optical flow visualization and sensor-based measurements. The findings are expected to help identify critical accumulation zones and may inform cabin design and safety regulations for future hydrogen-powered aircraft.

AI Use Case Profiling, Clustering, and System Decomposition for Compliance-Oriented ATM Applications

Ismini Stroumpou, Josep Lluis Larriba-Pey
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1. Introduction / Objectives

The rapid integration of Artificial Intelligence (AI) in Air Traffic Management (ATM) and airport operations offers significant efficiency gains but raises critical challenges related to trust, safety, and regulatory compliance. The EU AI Act and aviation-specific frameworks such as the EASA AI Roadmap require AI systems deployed in safety-critical infrastructures to be explainable, auditable, and continuously monitored. However, dedicated compliance mechanisms tailored to the ATM domain remain largely absent. The AIC4ATM project (HORIZON-SESAR-2025-DES-ER-03, Grant No. 101287448) addresses this gap by developing a modular AI Compliance Engine (CE) for ATM applications. This paper presents the methodological foundations underpinning the CE: a structured methodology for profiling and clustering AI use cases deployed or proposed in ATM, and a compliance-oriented decomposition framework for breaking down complex AI systems into auditable, traceable functional components based on the SESAR Target Architecture.

2. Methodology

AI use cases in ATM are systematically identified and profiled using a standardized attribute model that captures AI model type (e.g., deep learning, rule-based expert systems), level of autonomy, learning paradigm (supervised, unsupervised, reinforcement), data dependencies and provenance, system interfaces, maturity level, and operational environment. Technology-based categorization organizes use cases across four primary AI

families — Machine Learning (ML), Deep Learning (DL), Natural Language Processing (NLP), and Computer Vision (CV) — each further subdivided by learning paradigm and model architecture (e.g., convolutional neural networks, transformers, k-means clustering, deterministic policy gradients). Functional clustering complements this by grouping applications according to their operational role: perception (e.g., surface surveillance, airspace sectorization), decision-making (e.g., delay prediction, conflict detection and resolution), and interaction (e.g., controller–pilot data link communication). This dual-axis taxonomy, shown in Figure 1, forms a structured, multi-dimensional map that links AI implementation methods to ATM-specific objectives, SESAR flagship functions, and business capabilities. Building on the clustered use case profiles, a compliance-oriented decomposition methodology is applied to break down each AI system into discrete functional modules. Grounded in Enterprise Architecture (EA) and Service-Oriented Architecture (SOA) principles and formalized through Model-Based Systems Engineering (MBSE), the decomposition provides component-level granularity across six structural dimensions: (i) component identification (sensors, preprocessing pipelines, ML/DL models, decision engines, human–machine interfaces); (ii) interfaces and data flows (input sources such as radar tracks and flight plans; outputs such as alerts and recommended actions); (iii) functional dependencies (sequential and parallel processing logic); (iv) technology mapping (associating each module with its AI family and learning paradigm); (v) operational context (en-route vs. ground operations, traffic density, environmental constraints); and (vi) integration points (connections to legacy systems, external platforms, and stakeholder roles). A key output is the definition of compliance anchors — specific points within system components or SESAR architecture views where regulatory obligations can be systematically traced and operationalized — enabling structured assurance, lifecycle monitoring, and modular integration within the CE. Data collection employs technical documentation reviews, structured interviews with AI developers and ATM operators, analysis of SESAR project deliverables, and exploitation of the eATM Portal and OrbusInfinity platform.

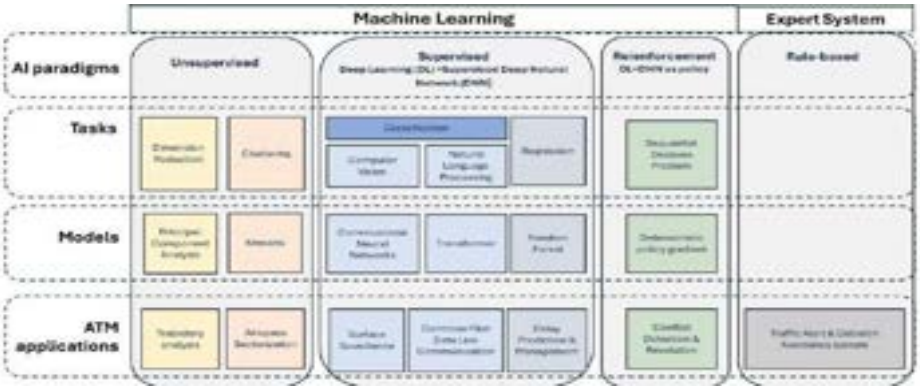


Figure 1. *Overview of AI-based technologies relevant for ATM,). Adapted from Du et al. (2025)*

3. Results / Conclusions

The use case profiling methodology yields a structured and harmonized dataset of AI applications in ATM, clustered by both technical and functional dimensions. The analysis surfaces early indicators of high-risk features — including opaque decision logic, elevated autonomy levels, and sensitive data handling — that directly inform the design of

compliance safeguards within the CE. This methodology sets the foundation for designing a decomposition framework producing a compliance-oriented, modular representation of AI systems, enabling systematic identification of explainability constraints, oversight gaps, and regulatory touchpoints at the component level. The definition of compliance anchors at targeted architecture establishes traceable links between system behavior, risk categories, and legal obligations, supporting dynamic querying, lifecycle monitoring, and automated compliance reasoning. Together, these methodological contributions establish the foundational analytical layer of the AIC4ATM Compliance Engine, advancing trustworthy and certifiable AI deployment in one of Europe's most safety-critical domains.

Pycnometer-Based Assessment of 3D Volumetric Measurements System for Nanosatellite Debris Characterization

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[1] R.tech, France
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1. Introduction / Objectives

The growing orbital debris population, together with the rapid rise in orbiting nanosatellites, calls for better characterization of the fragments these platforms may generate. To this end, a robotic stereoscopic 3D scanning system was previously developed to reconstruct debris and derive characteristic lengths, volumes, and densities. It was applied within CNES's T4SC program during two measurement campaigns on nanosatellite fragments produced in a dedicated fragmentation experiment.
Comparing the measured fragment properties with NASA fragmentation models revealed discrepancies. Some derived densities also appeared unrealistically low for the expected nanosatellite materials, highlighting the need to assess the current 3D-based volumetric method and explore complementary approaches.
In parallel, ongoing developments of NASA's Orbital Debris Engineering Model (ORDEM 4.0) place greater emphasis on debris shape , representing fragments as equivalent right circular cylinders (RCCs). Accurate volume determination is therefore a key input for shape-based debris characterization and model integration.

2. Methodology

To assess the limitations of the 3D-based volumetric method, ten nanosatellite fragments were selected for complementary measurement using a helium gas pycnometer. The fragments were chosen to cover a range of sizes, shapes, and materials, most of them selected on account of doubtful 3D-derived volumes identified in previous campaigns.
The robotic stereoscopic 3D scanning system acquires multiple views of each fragment by capturing stereo image pairs from different orientations, including the bottom face on which the object rests. Each acquisition produces a point cloud; the individual point clouds are first merged, then filtered to remove noise-induced points. The filtered point cloud is subsequently meshed to generate a surface representation of the fragment. A surface-closing algorithm then fills unscanned or masked regions to produce a closed mesh from which volume is

computed. Fragment mass, measured independently, is then combined with the reconstructed volume to derive density.
The pycnometer operates by injecting helium into a reference chamber of known volume up to a predefined pressure; a valve then allows the gas to expand into the sample chamber, and the volume of the solid is derived from the resulting pressure variation, knowing the chamber volumes and gas conditions. Each fragment was measured in three successive runs, and the mean value was retained.
Pycnometer-derived volumes and densities were compared with values previously obtained from robotic stereoscopic 3D scanning for each of the ten fragments. Discrepancies between the two methods were analyzed as a function of fragment morphology, in order to identify and distinguish between correctable deficiencies and intrinsic limitations of the 3D reconstruction chain.

3. Results / Conclusions

Volumes obtained from 3D reconstruction were higher than those measured by pycnometry, which led to underestimated densities. The pycnometer results were consistent with expected material families, while the comparison highlighted two dominant error sources: overestimation of thin thicknesses, and creation of artificial volumes when the surface-closing algorithm fills masked or non-scanned regions. These effects were especially severe for multilayer, folded, or highly occluded fragments. One small fragment fell below the pycnometer's measurement range, revealing a limitation of the instrument.
The pycnometer proved a robust reference for distinguishing intrinsic limitations from correctable deficiencies of the 3D chain. The results suggest several improvement paths for future campaigns: redesigning the scanning system to increase surface coverage; refining the reconstruction chain for thin features; defining criteria for when direct pycnometer measurement is required; and implementing hybrid campaigns combining both methods. They support enriching future debris characterization with complementary descriptors such as solidity or compactness.

Adaptive RAAN Based Optimization of Regional CubeSat Constellations Using a Time Regularized Revisit Metric

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Middle East Technical University (METU), Türkiye

1. Introduction

Small satellite constellations are increasingly attractive for affordable and responsive Earth observation, yet many preliminary designs still begin from globally symmetric Walker type patterns . For missions concentrated over a national region, such symmetry can allocate orbital planes inefficiently relative to the target geography. This work addresses this limitation by proposing an adaptive RAAN based optimization framework for regional CubeSat constellations, using Türkiye as a representative case study. The objective is to improve revisit performance while preserving a compact mission architecture. The scientific novelty lies in combining a target adaptive RAAN placement rule, a two stage integer composition search for distributing satellites among planes, and a Time Regularized Average Revisit Time (TRART)

metric that evaluates both access frequency and temporal coverage consistency, complementing recent studies on regional constellation optimization.

2. Methodology

A MATLAB based simulation and optimization environment was developed to evaluate candidate Low Earth Orbit CubeSat constellations over representative ground targets distributed across Türkiye. The total number of satellites is treated as a mission level design parameter; in the present study, a ten satellite fleet is considered. Candidate circular Sun-synchronous orbits are evaluated at altitudes of 400, 500, and 600 km with a fixed inclination of 97.6 deg. For each altitude, the number of orbital planes and the integer satellite distribution across planes are varied. The RAAN values are not assigned uniformly over 360 deg; instead, the proposed targe -adaptive rule bounds and places orbital planes according to the longitude envelope of the regional target set. The optimization is then performed in two stages. First, balanced plane allocations are screened to identify promising plane numbers. Second, all ordered integer compositions of the satellite fleet over the selected plane number are evaluated, allowing nonuniform allocations such as [3,1,3,2,1]. Candidate designs are assessed using conventional Average Revisit Time (ART), Türkiye Regional Average Revisit Time, instantaneous coverage, and the proposed TRART metric. TRART regularizes revisit assessment by rewarding observation opportunities that are distributed across multiple monitoring intervals, rather than clustered within a short time span. This makes the metric more suitable for applications such as disaster monitoring, agriculture, and environmental surveillance, where temporal regularity is operationally important. Overall, 592 candidate configurations are analyzed over altitude, plane number, and satellite distribution variables.

3. Results

The best performing configuration within the evaluated design space is obtained at 400 km altitude with five orbital planes and a nonuniform satellite allocation of [3,1,3,2,1]. This architecture achieves a Türkiye regional average revisit time of 6.46 h, an overall average revisit time of 7.54 h, and an instantaneous coverage value of 15.42%. The results indicate that regional, RAAN adaptive, and nonuniform constellation design can provide a more mission oriented alternative to globally uniform assumptions for geographically focused Earth observation. Beyond identifying a single solution, the proposed framework provides a repeatable methodology for evaluating trad -offs among altitude, fleet size, orbital plane allocation, coverage, and temporal revisit consistency.

Thermo-Structural Modeling of LH2 Tanks for Aircraft Design

Vishwanath Nagaraj, Francesco Orefice, Roelof Vos
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1. Introduction / Objectives

Liquid hydrogen (LH2) is increasingly seen as the most viable carbon-free energy source in

aviation, but several challenges remain unsolved before achieving safe and efficient integration in aircraft . A key step in making this a reality lies in ensuring that the analysis of the tank's structure is sized with sufficient accuracy to prevent major failures. This work is undertaken with the CRYOSTAR project , which aims to define a roadmap for the certification of LH2 tanks to crashworthiness. Within the project, this study aims to examine the impact of various loads and thermo-structural interactions on the cryogenic tank, and create structural sizing guidelines by comparing the impact that different static, dynamic and thermal loads have depending on dimensions and technologies of the storage system. An automated computational workflow is created to serve this purpose, and establish the appropriate level of fidelity for LH2 tanks in conceptual aircraft design.

2. Methodology

As part of a larger digital thread, a computational framework is created to automate preprocessing, meshing, and simulation control in a multiphysics solver, ABAQUS. In the sequential approach, the thermal simulation is carried out first, assuming a short time during which boil-off can be neglected. A fixed internal temperature is applied part of the tank in contact with the liquid fuel, and convective heat transfer is modeled for the part of the tank in contact with the ullage. The same is done for the outer surface of the tank, to represent heat leak to the external environment. Once the steady-state solution is obtained, the temperature distribution is used as an input for the structural simulation; which is critical to model the effects arising from the temperature-dependent material properties of the cryogenic tank. The coupled approach directly simulates both thermal and structural disciplines together, offering more accuracy for transient simulations but is computationally more expensive.

Mechanical loads on the tank are present in the form of internal pressure from the ullage, and reaction loads from the tank's retention system. The fuel's sloshing loads are omitted in order to preserve numerical efficiency. The retention system is not explicitly modeled, but loads transferred from here are modeled as fixed values for steady cases, applied to the appropriate location on the tank. Given the high complexity and cost of fully dynamic simulations, the equivalent static load method is adopted to capture the effect of transient loads onto the tank. Further modeling simplifications are tested in the form of using reduced-integration elements instead of true hexahedral elements in the structured mesh as seen in Bagarello et al , and the use of a symmetry boundary condition along the length of the tank. The resulting stress distributions are used to assess the viability of the tank's structure, and if needed, modify the design parameters to meet the required loads without failure. Alternatively, if the resulting stresses are lower the design capability, the structure's parameters are modified to increase the tank gravimetric efficiency while still meeting the load requirements.

3. Results / Conclusions

The computational framework in conjunction with the parametric studies help create design guidelines for temperature-informed structural sizing of cryogenic tanks. Figure 1 shows the stress distribution of the inner tank due to an internal pressure and the annular clamping of the retention system. The results of this study encompass different volumes and hydrogen masses to investigate the impact that the loads generated by standard maneuvers, pressure and temperature differences have on the sizing of the cryogenic tanks. While the pressure

and thermal loads are almost independent from the scale, the equivalent static load depends on the hydrogen tank and this study proposes a threshold value beyond which the error made by neglecting the maneuvering load is unacceptable, even at conceptual design level. This work lays the groundwork for the project Cryostar, but crash and sloshing loads are excluded from the scalability assessment presented.

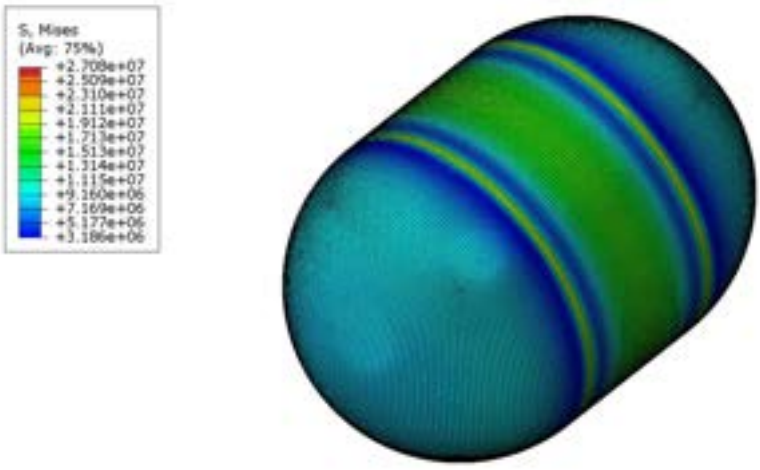


Figure 1. *An example result of the stress distribution over the inner tank due to a pressure differential of 2MPa and anular retention system clamping*

Bio-Inspired Wing Optimisation for Efficiency and Lateral-Directional Stability of a Vertical-Tailless Heavy Autonomous Glider

Francesca Barone, Erwin R. Gowree, Paraskevas Kalandronis, Maëlle Le Ménès Rego, Pedro D. Macedo Afonso, Tancredi M. Siragusa, Riki Toubkin
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1. Introduction

The design of high-efficiency vertical-tailless gliders for autonomous cargo delivery poses a fundamental aerodynamic challenge: maximising lift-to-drag ratio while ensuring lateral-directional stability without the drag penalty of a conventional vertical tail. Biological inspiration is drawn from the herring gull (*Larus argentatus*) and the peregrine falcon (*Falco peregrinus*), whose swept multi-segment wing planforms generate inherent directional stability through wing geometry alone . A central objective is the minimisation of induced drag, dominant in the drag budget of high-lift gliders. Bio-inspired planform geometries have been shown to achieve Oswald efficiency factors exceeding those of conventional planar wings by favouring spanwise lift distributions that spread vorticity both horizontally and vertically . This study investigates whether an optimised gull-wing and winglet configuration, sized for a 1000 kg MTOW glider with a wingspan in the 8–12 m range, can simultaneously maximise aerodynamic efficiency and provide inherent lateral-directional stability without a

vertical tail.

2. Methodology

The design is approached as a high-dimensional parametric optimisation. The wing geometry is fully described by a set of independent shape parameters covering both the main planform and the winglet geometry. Section aerodynamic data are generated by a dedicated in-house parametric aerofoil tool automating XFOIL-based polar computation. Three-dimensional aerodynamic and stability analyses are performed using AVL (Athena Vortex Lattice) and XFLR5, supplemented by semi-empirical viscous drag corrections. The optimisation is driven by an in-house multi-stage framework combining design space exploration, surrogate-assisted stability screening, and global search ranked by maximum lift-to-drag ratio.

Experimental validation is conducted in the low-speed wind tunnel at DAEP, ISAE-SUPAERO. Force, moment, and surface flow measurements across angles of attack and sideslip provide direct validation of computed stability derivatives and aerodynamic polars. Beyond validation, the experimental campaign is expected to shed light on the aerodynamic behaviour of bio-inspired non-planar wing configurations.

3. Results

Preliminary results indicate that gull-wing configurations satisfying lateral-directional stability requirements exist within the design space. The swept multi-segment planform combined with outward-canted winglets provides the directional restoring moment conventionally supplied by a vertical tail , while the non-planar geometry is expected to contribute simultaneously to induced drag reduction, consistent with the vorticity spreading mechanism identified in bio-inspired configurations . Optimised designs are projected to achieve vehicle lift-to-drag ratios of 10–15 at cruise.

Bio-morphing Deployable Tail Plane Options for Longitudinal, Lateral and Directional Control of Compact Stowage Autonomous Heavy Glider

Francesca Barone, Erwin R. Gowree, Paraskevas Kalandronis, Maëlle Le Ménès Rego, Pedro D. Macedo Afonso, Tancredi M. Siragusa, Riki Toubkin
ISAE-SUPAERO, France

1. Introduction

Compact-stowage gliders require deployable aerodynamic surfaces that can be efficiently packaged while ensuring reliable flight performance after deployment. This work presents a bio-inspired morphing tailplane concept in which the conventional horizontal and vertical stabilizers are replaced by a single deployable part inspired by avian tails. The proposed architecture is a morphing trapezoidal tailplane that can transition from a flat configuration to an inverted-V geometry, enabling the same surface to provide both longitudinal and directional control while minimizing stowed volume. Particular attention is given to addressing

the challenges associated with deployable empennage systems, balancing aerodynamic effectiveness, mechanical simplicity, deployment reliability, and control authority in terms of longitudinal and directional dynamics. Part of the investigation also concerns whether the proposed morphing tail architecture can additionally provide roll control authority, potentially reducing the need for dedicated control surfaces. The study describes the design methodology and evaluates the aerodynamic and stability characteristics of the concept, demonstrating the potential of bio-morphing tail architectures as an efficient solution for future compact deployable gliders.

2. Methodology

The proposed methodology consists of a progressive aerodynamic and stability analysis of the morphing tail configuration, combining literature review and numerical modelling tools. First, the tail geometry is parameterized by defining a range of morphing states, from a flat tail configuration to different inverted-V angles. Aerodynamic and static stability analyses are then be performed using XFLR5 to evaluate the influence of the morphing angle on the aircraft's longitudinal, directional, and lateral stability characteristics. Subsequently, more detailed investigations are carried out using AVL (Athena Vortex Lattice) to determine stability and control derivatives, allowing the effects of both symmetric and differential tail deflections to be quantified. Particular attention is given to the variation of directional stability, roll–yaw coupling, and control effectiveness as the tail transitions between configurations. The results obtained from the different morphing states are compared to identify potential aerodynamic and stability advantages of the concept and to assess its suitability as a multifunctional stability and control surface for glider applications.

3. Results

The expected outcome of the work is to identify how the morphing mechanism can be used to continuously tailor lateral-directional stability characteristics and handling qualities, potentially enabling adaptive stability management in glider configurations.

Assessment of Structural Requirements for Building a Lunar Habitat

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1. Introduction / Objectives

In pursuit of establishing a sustainable lunar settlement, the need for efficient construction and resource utilization on the Moon has become increasingly critical. Early construction materials that offered durability, such as Sulphur, Cast Basalt, and Geopolymer, required not

only complex manufacturing infrastructure but also continuous resupply from Earth. Purely inflatable structures enable rapid deployment but have a lower shelf-life due to degradation under prolonged environmental exposure.
This paper proposes a Hybrid Inflatable Lunar Habitat System, seen in Figure 1, comprising: an inner inflatable module with indigenous material selection, which can be rapidly deployed, a Fe-based shape memory alloy (SMA) spaceframe informed by in-situ resource utilization (ISRU) of Iron derived from the lunar regolith using an electrolysis process, to support an exterior regolith layer while preserving necessary expansion gaps. This study emphasizes the protection of astronauts by assessing the habitat system's durability in harmful radiation, extreme thermal variations, and vacuum conditions on the lunar surface, practicing sustainability and lower reliance on transported Earth supplies.

2. Methodology

1. The first step delves into the geometric optimization of the habitat for minimal ground surface area, and for a fixed volume. A combination of Bracketing and Newton-Raphson's method was implemented to solve the complex equations and ensure accurate results of the parameters.
2. The two design approaches of Integral and Modular architecture were established, represented by a material configuration by and the proposed lunar habitat system, respectively, for a structured assessment in the developed lunar environment models.
3. The material selection for the innermost inflatable module of the modular system was inspired by , with significant modifications such as the addition of Vectran and Boron carbide to the material layering through iterative re-design based on simulation results.
4. Iron extracted from lunar regolith through electrolysis, based on research by Alexandra Radl in , was utilized as Fe-SMA spaceframe. The material's Shape Memory Effect (SME) and Pseudoelasticity were examined in COMSOL to assess its structural support and MMOD shielding capabilities.
5. The outermost regolith layer was characterized using established lunar simulants developed by JSC (Johnson Space Center) to replicate the thermal and radiation properties of natural lunar regolith.
6. Thermal simulations in COMSOL, coupled with radiation assessments in NASA's OLTARIS, mainly Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPSs), examined the efficacy of integral and modular habitat designs as well as individual components for withstanding the Moon's harsh environment.



Figure 1. *Conceptual illustration of the proposed lunar habitat system.*

3. Results / Conclusions

1. Circular geometries (prolate spheroid, sphere, etc.) minimize material usage, as supported by the isoperimetric theorem.
2. The proposed material design provides gradual and consistent thermal insulation across multiple layers by reducing thermal concentration at the outer surface. The vacuum-pressed regolith as the outermost layer of the habitat system provides exceptional thermal isolation, maintaining room temperature for the crew in the innermost layer.
3. The integration of boron carbide and rearranged layers with Aluminum, UHMPE, and Vectran in the material configuration shields protons, neutrons, and other particles effectively, even under extreme GCR and SPE conditions. The entire habitat system provides radiation protection as per the permissible levels described in NASA STD 3001 Volume 1 .
4. These findings advance resilient extraterrestrial construction technologies and lay a solid foundation for future design iterations of lunar outposts.

Ice detection and automatic activation of a resonant electro-mechanical de-icing system using piezoelectric impedance and machine learning

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1. Introduction / Objectives

Ice accretion is a major safety risk in aviation which requires aircraft to be equipped with anti-icing or de-icing systems. In the context of electrification of aircraft, systems that depend on thermal engines may become obsolete, opening the way for new electrical architectures. Among the emerging alternatives, electro-mechanical resonant de-icing systems rely on piezoelectric actuators to vibrate the leading edge at one of its natural frequencies and trigger ice detachment. De-icing of the leading edges was successfully demonstrated in icing wind tunnels . However, in these experiments, the system was triggered manually after a sufficient amount of ice was accreted. This method is not compatible for in-service use. The objective of the present work is therefore to guarantee an continuous and automatic operation of the resonant de-icing system using the de-icing system actuators to detect the presence of ice and trigger the actuators at the appropriate moment.

2. Methodology

2.1 General approach

A study case is first selected, defining the structure's geometry and material. This study is

intentionally conducted on a simplified geometry to facilitate the development of activation logic concepts before extending the method to more complex structures. The proposed methodology is described in Figure 1. Based on this case and a design of experiments (DOE) describing various ice conditions, a synthetic dataset is generated with a finite element model and used to train and validate a machine learning regressor trained for ice detection. During the test stage, the piezoelectric actuator impedance is measured on the instrumented structure. The parameter identification yields the modal parameters of the real structure. The regressor then predicts the de-icing voltage from these parameters, a drop in voltage indicating the presence of ice.

2.2 Generation of the synthetic dataset

As a first step, a simple parallelepiped-shaped ice accretion with varying density , thickness and length is considered. The approach is evaluated on three resonance modes of interest: the first flexural mode (Fig 1. (a)), the first in-plane flexural mode (Fig 1. (b)) and the first extensional mode (Fig 1. (c)). The use of different kind of modes is beneficial because it increases the size of the database and the number of features. Each instance in the dataset is described by two features (resonance frequency and modal mass) and labelled by the corresponding de-icing voltage.

2.3 Training & Evaluation

Several supervised learning techniques are compared, including support vector machines and random forests, trained to predict the voltage required to initiate ice fracture. Cross-validation is used to assess the performance of each algorithm and to select the best-performing model. Performance is evaluated using the root-mean-square error (RMSE) — quantifying the accuracy of the predicted de-icing voltage against the finite element reference.

2.4 Experimental validation

Finally, the detection and activation chain will be validated experimentally on the test bench, under controlled icing conditions reproducing various ice thicknesses and shapes. The objective will be to assess the robustness of the approach using experimental data and to go beyond the synthetic training set.

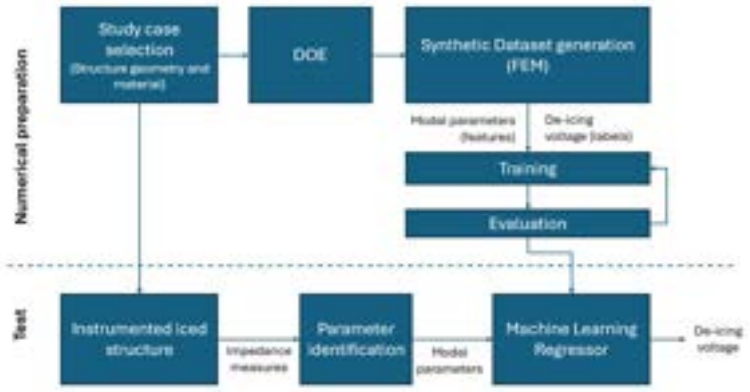
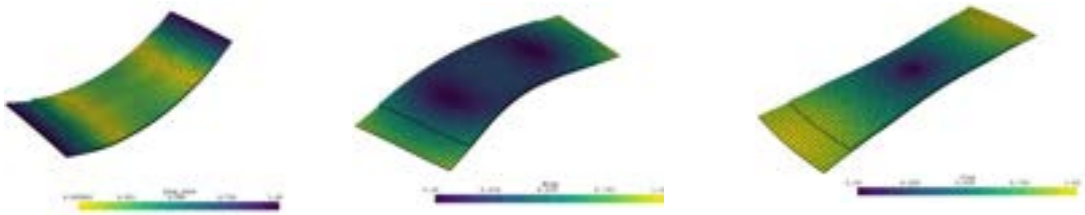


Figure 31. De-icing voltage prediction methodology



(a) (b) (c)

Figure 2. Mode shapes of the plate with a layer of ice on top. (a) 1st flexural mode 603Hz, (b) 1st in plane flexural mode 10.8kHz, (c) 1st extensional mode 20.1kHz

3. Results / Conclusions

Reliable ice detection is crucial for ensuring the safety of aircraft and improving the energy efficiency of de-icing systems. This study proposes a method of ice detection and de-icing system activation based on the estimated de-icing voltage, as determined by a machine learning model using admittance measurements performed directly on the de-icing system actuators. This dual use of the piezoelectric transducers — for both sensing and ice removal — opens the way for a fully autonomous, sensor-free ice protection system, with potential gains in mass, integration simplicity and detection coverage at the aircraft scale.

Multidisciplinary Integration of High-Fidelity Models in the Preliminary Design of a Box-Wing DEP Aircraft

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1. Introduction

This work addresses the multidisciplinary design and refinement of a hydrogen-powered regional aircraft featuring a box-wing configuration and distributed electric propulsion (DEP). The main objective is to integrate high-fidelity aerodynamic, structural, and propulsion models into the preliminary aircraft design process. The study focuses on capturing the synergistic effects between box-wing aerodynamics and over-the-wing distributed propulsion, enabling a more realistic assessment of aircraft performance, efficiency, and sustainability compared with conventional regional aircraft concepts.

2. Methodology

High-fidelity aerodynamic models derived from computational fluid dynamics (CFD) simulations and wind-tunnel experiments are incorporated into the aircraft sizing and mission-analysis framework on the Aircraft Design tool SUAVE. Aerodynamic characteristics and conceptual wing-structure results are transferred into the overall design environment and coupled with structural and propulsion-system models presented in the work of . Particular attention is given to modelling the interaction between distributed propellers and the box-wing configuration, including their effects on lift generation, induced drag reduction, propulsive efficiency, climb performance, and aircraft energy demand. Sensitivity studies and trade-off analyses are performed to evaluate the influence of technology integration levels, subsystem positioning, and aerodynamic assumptions on overall aircraft behavior and operational characteristics.



Figure 1. *Schematic figure of DOXWING concept*

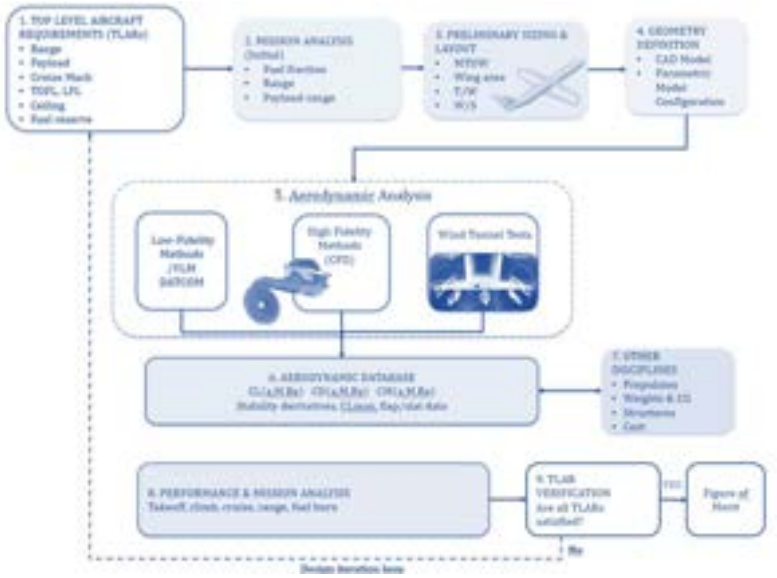


Figure 2. *Overall aircraft design assessment methodology*

3. Conclusions

The integrated methodology and extended design tool enable the definition and assessment of the final DOXWING aircraft configuration. Results indicate that combining box-wing aerodynamics with distributed electric propulsion with hydrogen fuel cell propulsion architecture can provide beneficial interactions affecting aerodynamic efficiency, energy consumption, mission performance, and noise-emission reduction in EIS year of 2045. The study demonstrates the value of multidisciplinary, high-fidelity model integration during preliminary aircraft design and supports the development of future sustainable regional aviation concepts.

Aerothermodynamic Shape and Material Assessment for Environmentally Sustainable CubeSat Re-entry

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1. Introduction / Objectives

The rapid growth of small satellite constellations has led to the uncontrolled atmospheric re-entry of satellites and upper-stage launch vehicles. The ablation and oxidation of structural materials, particularly aluminium, generate alumina particles and nitrogen oxides, contributing to catalytic ozone depletion and atmospheric pollution; an issue with limited mitigation strategies. This paper proposes an autonomous re-entry add-on module, in accordance with the Design for Non-Demise concept , to enable controlled descent and vehicle survivability without replacing existing material technologies. The scope of the

present study focuses on the architecture of the add-on module, comprising a combination of inflatable and ablative materials to shield the vehicle while being autonomously propelled by the Water Electrolysis Propulsion (WEP) system. This study examines the geometric and material configuration to minimize thermal loads and material ablation during hypersonic atmospheric entry.

2. Methodology

The study adopts a multi-stage simulation framework to evaluate hypersonic module configurations for environmentally responsible satellite re-entry.

1. Initially, orbital decay and atmospheric entry trajectories are modelled in MATLAB to estimate aerodynamic deceleration and heating exposure, to determine peak thermal loads for different geometries. These heating conditions are then used as boundary inputs for thermal response simulations of candidate materials.
2. To further examine the influence of geometry on hypersonic flow behavior, computational fluid dynamics (CFD) simulations are conducted in ANSYS Fluent and ballistic coefficients and survivability in the OSCAR module of ESA's DRAMA for representative configurations. The geometric CFD results are paired with material selection for a flexible heat shield to protect the vehicle with limited outer-layer ablation. These candidate high-temperature materials will undergo thermal gradient analysis in COMSOL.
3. In parallel, the thrust requirements for different CubeSat classes are estimated using a water electrolysis propulsion model developed to correlate thrust generation, onboard water propellant capacity, and CubeSat mass class.
4. Finally, the survivability and breakup characteristics of the candidate configurations are evaluated using the SARA module of ESA's DRAMA tool to estimate demise altitude and surviving mass fraction.

3. Results / Conclusions

1. The proposed module demonstrated viable thermal and aerodynamic performance for controlled CubeSat re-entry. Trajectory and CFD simulations showed that blunt and hyperbolic inflatable geometries reduced peak thermal loads by increasing shock stand-off distance and lowering ballistic coefficients during atmospheric re-entry.
2. Thermal analysis indicated that multilayer flexible thermal protection systems using ceramic fabrics and aerogel insulation minimised heat penetration and reduced outer-layer ablation. This contributed to lowering the predicted formation of alumina particles and nitrogen oxide precursors associated with uncontrolled satellite re-entry.
3. Preliminary modelling indicates that water electrolysis propulsion can provide adequate thrust for controlled CubeSat de-orbit and orbital manoeuvring missions.
4. ESA DRAMA survivability analysis indicated reduced uncontrolled fragmentation and improved controlled recovery potential. Overall, the findings support the viability of

combining deployable aerodynamic deceleration, flexible thermal protection systems, and autonomous propulsion for sustainable CubeSat atmospheric re-entry.

The Harvard-Autonomous Architecture: Decoupling Safety from Intelligence in AI-driven Flight

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1. Introduction / Objectives

Autonomous flight is held back less by broken hardware than by functional failure — a healthy learned system that simply decides wrong. A planner facing an unfamiliar situation can commit to a maneuver that looks correct at every instant yet leaves the safe envelope seconds later. Triple-modular redundancy cannot help: identically trained networks share the same blind spot, and the voter only confirms it . Signal-level runtime monitors cannot separate a momentarily plausible plan from a fatal one without becoming planners themselves. We introduce the Harvard-Autonomous Architecture (H-AA): a certifiable autopilot keeps sole authority over the actuators, while a learned co-pilot only proposes plans, validated over their full trajectory before execution. Our objective: show that this plan-level separation lowers the catastrophic-failure rate while raising mission success — beyond the kinematic safety envelopes of automotive autonomy.

2. Methodology

H-AA splits the system into two domains (Figure 1). The safety domain is a deterministic, certifiable autopilot performing instrumental navigation along a pre-loaded path; it is the only component wired to the actuators. The mission domain is a learned co-pilot — vision, navigation and reactive path planning — that emits intentions (plans from a finite, typed vocabulary) rather than control signals. The PAC-D protocol couples them: a deterministic validation contract checks each proposed intention over its trajectory horizon; on rejection, or on loss of the co-pilot's heartbeat, the autopilot simply continues on its own plan. The aircraft is therefore never worse off than the bare autopilot.

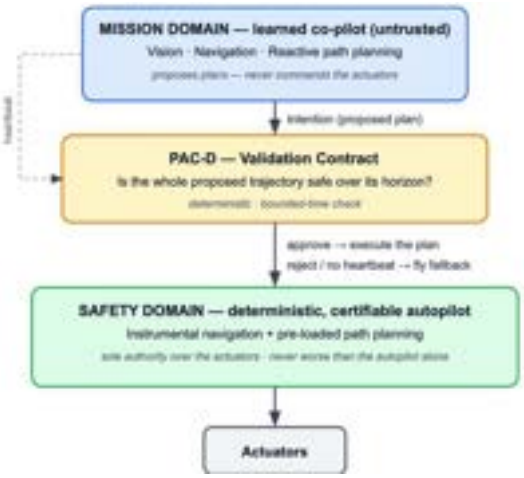


Figure 1. *The Harvard-Autonomous Architecture*.

We assess the architecture from three complementary angles. (A) Analytical. We write each architecture's catastrophic probability in closed form and build a fault tree following ARP4761A/ARP4754B ; this shows that in H-AA a wrong plan is not, by itself, a catastrophic cut-set — it must coincide with a failure of the contract. We prove soundness for one worked predicate, terrain clearance, where membership in a pre-computed reachable envelope (a control-barrier-style certificate) guarantees the trajectory stays safe under worst-credible disturbance. (B) Reliability sensitivity. TMR, COM-MON (strict and relaxed) and H-AA are modelled as stochastic processes; we sweep the common-mode correlation and the monitor strictness by Monte Carlo and report catastrophe, mission-success and abort rates — as a sensitivity study of the trade-off, not a demonstration of an absolute target. (C) Closed-loop simulation. Reactive scenarios — a canyon turn, an urban-air-mobility corridor and a snowy runway — are flown in a closed loop built on PX4 SITL, AirSim and ROS 2 , with the two domains as separate processes and faults injected blind to the architecture under test. We contrast H-AA with Simplex- and shielding-style baselines ; models are calibrated where possible against reported correlated-failure rates , with CoDANN and ISO 21448 (SOTIF) framing learning assurance and the functional-insufficiency hazard.

3. Results / Conclusions

The three methods agree. Under correlated, functional failure the classical architectures either lose safety — TMR's catastrophic rate grows with the correlation — or, once tightened, abandon the mission. H-AA instead holds the catastrophic rate bounded and converts a wrong decision into a controlled abort, paying only with a graceful rise in the mission-abort rate while preserving reactive intelligence. We quantify this cost of decoupling as the abort/success price relative to the other designs. The conclusion is that safety against functional failure is an architectural property, not a redundancy one: it belongs at the level of whole plans, guarded by a competent autopilot that can always fly on its own. Beyond aviation, the same pattern — a learned proposer behind a deterministic, plan-level gate — offers a certifiable route to coupling foundation-model autonomy with any safety-critical physical system.

Novel Hybrid Approach of Metal Leading Edge Manufacturing Combining Forging and Laser Powder Directed Energy Deposition

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1. Introduction / Objectives

The manufacturing of metal leading edges (MLE) for aerospace applications, typically thin-walled Ti-6Al-4V structures with high aspect ratios, relies on subtractive processes generating large machining volumes and high resource consumption . Additive Manufacturing, such as Laser Powder Directed Energy Deposition (DED-LB/P) offers a pathway to reduce material waste and energy input, with demonstrated reductions in energy consumption and CO_2

emissions of over 60% . However, applying DED-LB/P to geometrically complex hybrid substrates, such as forged MLE blanks with surface inclinations exceeding ±90°, has not been demonstrated as a continuous process chain. The present work addresses this gap by combining closed-die forging with DED-LB/P to produce Ti-6Al-4V MLE geometries. The objectives are: (1) to establish a stable process for deposition on curved substrates; (2) to develop an optimized build-up strategy for thin-edge geometries; and (3) to demonstrate feasibility through manufacture of a simplified MLE prototype.

2. Methodology

Experiments are conducted using a TruLaserRobot 5020 (Trumpf, Ditzingen, Germany) equipped with a KUKA KR60 HA industrial robot and a DKP 400.1 two-degree-of-freedom external positioner, enabling flexible substrate orientation during deposition. A HIGHNO 4.0 coaxial powder nozzle (HD Sonderoptiken, Germany) ensures a stable, continuously coaxial powder stream. Ti-6Al-4V ASTM Grade 5 powder (20–63 µm, Eckert TLS, Germany) is used throughout all experiments. To prevent oxidation of the deposited Ti-6Al-4V layers, a custom local shielding gas system is developed and integrated into the setup, achieving residual oxygen levels below 80 ppm at 25 L/min argon flow. All experiments employ a consistent parameter set derived from preliminary optimization: laser power 650 W, scan speed 10 mm/s, powder mass flow rate 2.25 g/min, working distance 9 mm, and a laser beam diameter of 1.5 mm, yielding a line energy of 65 J/mm. The experimental program is structured in four successive series, each building on the prior:

– Series I quantifies the influence of substrate inclination (30°-80°) on single-track geometry regarding the width, height and melt pool peak shift, while the processing head maintained orthogonal to the substrate throughout, establishing reference values for subsequent tests.

– Series II investigates deposition of material volumes along a thin rounded substrate edge, developing the fundamental approach for the leading edge built-up.

– Series III realizes a full volumetric deposition enclosing the edge geometry from both sides and from the top, assessing layer interaction, bonding quality, and geometric consistency.

– Series IV transfers the validated build-up strategy with iterative refinements for demonstrator manufacturing.

Metallographic cross-sections are prepared and analyzed using a Keyence VHX-5000 optical microscope to assess internal defects (porosity, bonding errors). Geometric dimensions are evaluated using a Wenzel LH87 CMM system.

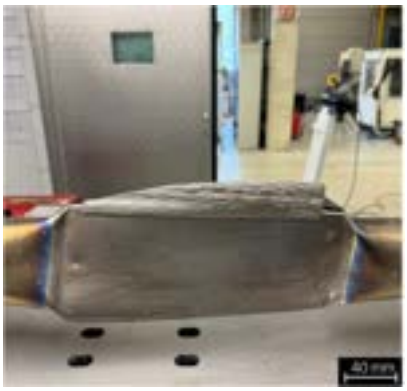


Figure 1. *As-built condition of the manufactured MLE demonstrator.*

3. Results / Conclusions

Series I confirms that substrate inclinations up to 80° produce no significant change in single-track geometry: track width varies by less than 1.6% relative to the horizontal reference, with no cracks, defects, or porosity detected. This validates the parameter set for angled forged substrates. Series II - III establish a viable multi-pass deposition strategy, with metallographic analysis revealing no cracks, no systematic bonding defects, and no continuous intolerable porosity. Geometric deviations of −2.5 to +3 mm are attributed primarily to workpiece registration inaccuracies; near-net-shape geometry achieved in the bulk of the deposit. Strategy refinements during series IV reduce processing time from 2 h 30 min to 1 h 58 min. The 243 mm free-form MLE geometry is successfully realized (Fig. 1), confirming the feasibility of the hybrid process chain. Future work will address mechanical property characterization, microstructural analysis, dimensional qualification, and influence of heat treatment routes on the demonstrator.

Coupling Cabin Layout and Fleet Transition: Interactive Analysis of Network-Level Fuel-to-PAX Ratio

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1. Introduction / Objectives

Cost per passenger (per-PAX) is a crucial operative metric in commercial airline economics with fuel burn being one of the substantial drivers. Due to the direct influence through fuel price as well as indirect cost through e.g. emission pricing instruments like ETS carbon surcharges, the resulting Fuel-to-PAX ratio is a central efficiency KPI for both network and fleet planning decisions . This ratio is governed primarily by cabin layout: the number of revenue passengers sharing a fuel amount is determined by seat count, class mix and zone allocation. Fleet composition is a downstream consequence of this relationship: when seats per aircraft change, both the viable aircraft types on a route and the required flight frequency shift accordingly. Therefore, a substantial challenge arises to assess the impact of fleet transitions either caused by typical retrofitting of cabins or the fleet induction of novel aircraft concepts.

2. Methodology

This work proposes an interactive exploration tool with online analytic capabilities that treat cabin layout and fleet composition as free variables for assessing the impact on route- and fleet-level Fuel-to-PAX ratios for a given operators flight network. The tool is formed by a process pipeline, as shown in Fig. 1: Initially, an existing operator's flight route network is extract from real-world data (Eurocontrol ADRR) for a given timeframe and resolved against ICAO type designators (FAA Aircraft Characteristics) to obtain the fleet composition and the specific aircraft morphology. In the subsequent step, a user can adjust the cabin layout interactively, as shown in Fig 1. These newly defined aircraft configurations, grounded in CPACS attributes , are passed to a fleet re-combination interface, that allows to define a fleet replacement scheme. The fuel-burn values are calculated based on these inputs using an implementation of the ICAO ICEC methodology. While this already forms the result for the typical retro-fitting investigations, an extended mode is available for investigating new propulsion systems. Therefore, the Jet-A1 fuel-burn value is mapped to e.g. LH2-equivalent via energy conversion and propulsion efficiency assumptions, enabling a back-of-the-envelope calculation to test design scenarios in an interactive way. The case-study demonstrates use of the tool on two real-world examples: (i) a **base case** (A380 cabin retrofit) in which cabin remodeling of an existing Jet-A1 fleet shifts per-PAX emissions and route capacity; and (ii) an **extended case** in which a transition to H2 propulsion is evaluated with the cabin volume–capacity trade-off (Airbus ZEROe concept, tanks within cabin).

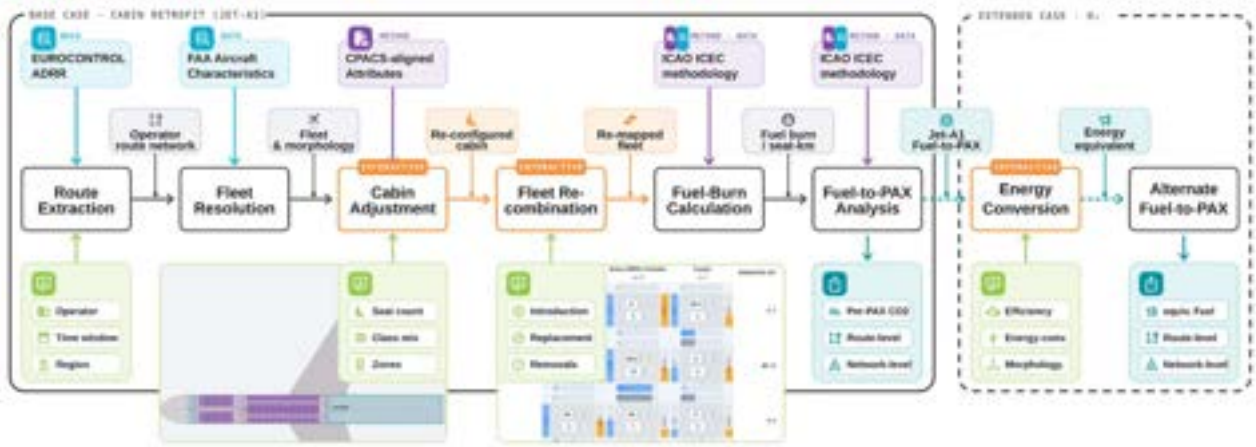


Figure 1. *Tool pipeline with highlighted data sources and user interactions for fuel-to-passenger sensitivity analysis.*

3. Results / Conclusions

The case study clearly shows the network-level impact of cabin-layout decisions, especially in the context of transitioning to decarbonized aviation, highlighting the importance of coupling cabin geometry and fleet transition analysis. While fuel-burn and cabin-configuration modeling do not feature the high fidelity of related tools focusing on e.g. segmented trajectories or in-depth cabin layouts, it provides valuable insights at early stage considerations due to the instantaneous results on a network-level, thanks to direct coupling of modern user-facing inputs and the high performance online analytical processing (OLAP).

Shortest route method adaptation for a planetary rover motion with slope limitation based on Mars Express topographic data

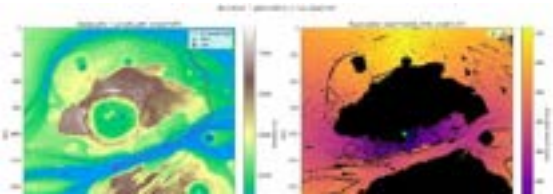
Aleksandrs Kuzevanovs[1], Vladislavs Vasiljevs[1], Anna Litvinenko[2], Sergejs Bratarcuks[1]
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1. Introduction / Objectives

Space science missions require detailed planning due to significant communication delays between Earth and spacecraft. For planetary rovers, autonomous path planning is particularly important because terrain conditions directly affect mission success. Current rover navigation research extensively investigates path-planning algorithms such as A* and graph-based navigation methods for autonomous mobility on planetary surfaces . However, quantitative assessments of how traversable slope constraints affect route quality and accessibility on high-resolution Martian topography remain relatively limited.
The objective of this work is to evaluate how maximum traversable slope affects path efficiency and reachability in the Sharonov crater region of Mars and to compare the performance of A* and a hybrid planning framework combining Dijkstra-based reachability analysis with Theta*-based route generation under identical terrain conditions. While previous studies have primarily focused on algorithm development and validation, this work applies both approaches to a realistic Martian topographic dataset and quantitatively evaluates their performance over a wide range of slope constraints.

2. Methodology

A blended digital elevation model (DEM) of Mars derived from Mars Orbiter Laser Altimeter (MOLA) and High-Resolution Stereo Camera (HRSC) data was used in this study . The source map has a spatial resolution of 200 m per pixel. A region measuring 2000 × 2000 pixels (400 × 400 km) around the Sharonov crater in the MC-10 Lunae Palus quadrangle was selected as the study area. The DEM was converted into a height matrix and used as the basis for path-planning simulations.
For each terrain cell, local slope values were calculated from elevation differences between neighboring pixels. Traversable areas were determined according to a maximum allowable slope threshold. The threshold was varied from 1° to 20° in 1° increments, from 20° to 50° in 5° increments, and from 60° to 90° in 10° increments to evaluate the influence of rover climbing capability on route-planning performance (see Figure 1).
A set of 200 random start–goal pairs was generated within the study area and used throughout the experiment. The same 200 routes were evaluated for every slope threshold and for both path-planning approaches, ensuring a direct comparison under identical conditions. A* and a hybrid approach combining Dijkstra-based reachability analysis with Theta*-based route generation were then used to compute an optimal route for each start–goal pair while respecting the specified slope constraint.
Algorithm performance was evaluated using route reachability, total path length, and path efficiency. Reachability was defined as the number of successfully generated routes. Path efficiency was quantified as the ratio between the computed path length and the corresponding straight-line (vector) distance between the start and goal positions. Values



closer to one indicate more direct routes. The resulting metrics were aggregated for each slope threshold and compared between the two planning approaches.

Figure 1. *Topography + sample path and reachability map for the 10° increment using A* algorithm.*

3. Results / Conclusions

Both algorithms demonstrated similar reachability across all tested slope thresholds, indicating that rover reachability was determined primarily by terrain constraints rather than the planning method. However, the hybrid Dijkstra–Theta* approach consistently generated more efficient routes. The average path length was reduced by approximately 3.6%, and the ratio of path length to straight-line distance decreased from 1.156 for A* to 1.114 for the hybrid approach. The largest differences were observed at low slope thresholds, where terrain constraints forced significant detours around steep sections. As the allowable slope increased, both algorithms generated increasingly direct routes, although the hybrid Dijkstra–Theta* approach retained a measurable advantage. This improvement came at the cost of greater computational complexity, as the hybrid approach required longer execution times and greater computational resources than the conventional A* algorithm.

These results demonstrate that combining global terrain reachability analysis with any-angle path planning can improve route efficiency without reducing terrain reachability. The obtained results can aid in the design of future Mars rovers and mission planning by providing quantitative estimates of how terrain traversability and route-planning strategies affect navigation performance on realistic Martian terrain. The observed trade-off between route quality and computational cost should be considered when selecting a planning approach for future autonomous rover missions.

ANALYSIS OF THE STIFFNESS AND DYNAMIC PROPERTIES OF THE WINGS OF DYNAMICALLY SCALED MODELS AND A REFERENCE AIRCRAFT

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1. Introduction

A fundamental requirement for building scale models of newly designed aircraft for flight performance testing is achieving dynamic similarity, resulting from scaling dimensions and masses. This is relatively easy to achieve, provided that specific similarity values for geometry and mass scaling are maintained. An additional requirement, much more difficult to achieve and therefore not always met, is ensuring stiffness similarity. This article presents the results of comprehensive research, a continuation of work presented by the authors at the EASN 2025 conference. The article discusses the impact of structural stiffness scaling, achieved by

imposing similarity conditions, on the torsional and flexural stiffness parameters of the wing structure.

2. Methodology

This work provides an example of utilizing selected advantages of composite technologies to design structures with the required properties. The airframe of the reference aircraft is made of metal, and its scale model is assumed to be a purely composite structure. Both the actual wing and the wing model were designed and built as part of research and development projects conducted at the Faculty of Mechatronics, Armament, and Aviation of the Military University of Technology. The reference aircraft is a light general aviation aircraft with a maximum takeoff weight of 850 kg and a wingspan of 8.5 m. The aircraft model is made in 1:2 scale, with a maximum takeoff weight of 105 kg. The structure of the actual wings is made of riveted aluminum alloy sheets, while the wing model is made of epoxy-carbon composite laminated by hand in a previously designed mold. The bending and torsional stiffness of the reference wings was calculated, and based on these calculations, the model structure was designed while maintaining the conditions of dynamic similarity.
To validate the method, comparative wing stiffness measurements were performed. Both wings were supported and loaded identically, and the deflection and twist angle values were measured in successive profile sections along the span. The obtained results were compared as dimensionless quantities.

3. Results

The analysis confirmed the similarity of the deflection lines and the distribution of twist angles. The similarity in deflection and twist confirms the possibility of adjusting the wing stiffness of the model by scaling individual parameters relative to the stiffness of the actual scale structure. Additionally, numerical modal analyses of the tested wing models were conducted, along with a comparative analysis of their dynamic properties.
This work illustrates the application of composite technologies and numerical techniques to design structures with the required properties. The airframe of the reference aircraft is made of metal, while its scale model is a composite structure. Both the wing and the wing model were designed and manufactured as part of research and development projects conducted at the Faculty of Mechatronics, Armament and Aviation of the Military University of Technology.

Turbo-engine tests with various SAF: Impact on non volatile Particulate Matter (nvPM) characteristics

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1. Introduction / Objectives

The aim of the present work is to contribute to the characterization at the exhaust of soot

properties in terms of nvPM mass (nvPM_mass) and number (nvPM_num) as well as nvPM diameter (nvPM_diam), resulting from the combustion of two fuels with very different chemical properties: pure SAF (Hydro-processed Esters and Fatty Acids / Synthetic Paraffinic Kerosine, HEFA/SPK), known as ARO-0% and a blend of SAF (48%) and Aromatics (52%), known as ARO-52%, as well as a BLEND of SAF (32 %) and Jet A-1 (68 %). Tested fuels were provided by TotalEnergies.

2. Methodology

These tests were carried out on the BEARCAT test bench (*Banc d'Essai Avancé pour la Recherche en Combustion et Aérothermique des Turbomachines*, **figure 1**) developed and operated by SAFRAN-Tech, the Safran Group Research Center. BEARCAT is based on a MAKILA, a turboshaft developed by Safran Helicopter Engines.
nvPM_mass, nvPM_num and nvPM_diam distributions are measured at the exhaust by means of an AVL MSS (Micro Soot Sensor ™ and AVL Particle Counter (APC) devices and a DMS-500 apparatus from Cambustion, respectively. We also measured the Smoke Number thanks to engine smoke measuring equipment from Richard Oliver LTD. Measurements are performed at the same time in the same plane of the exhaust detuner, approximately 4 m downstream of the engine exhaust nozzle, during stabilized conditions, from idle to maximum power allowed.

3. Results / Conclusions

In this paper, we will first present the variation of key soot parameters (nvPM_mass, vnPM_num and nvPM_diam) as a function of engine operating conditions (i.e., fuel flow rate), then we will examine how these parameters depend on one another, and how results obtained with ARO-52% corralled with previous results.
As example, **Figure 2** shows the evolution of nvPM_mass (left) and nvPM_num (right) vs. Engine Speed. Red dots correspond to previous tests. They clearly show the reproducibility of the results. As expected, for all fuels tested, nvPM_mass and nvPM_num are both increasing with the engine speed. However, ARO-52% exhibits specific behaviors. Its nvPM_mass reaches a maximum value while its nvPM_num start to decrease at the same condition, leading to a saturation effect on the Smoke Number, despite the increase of nvPM_diam with the engine speed.



Figure 1: *BEARCAT test rig*

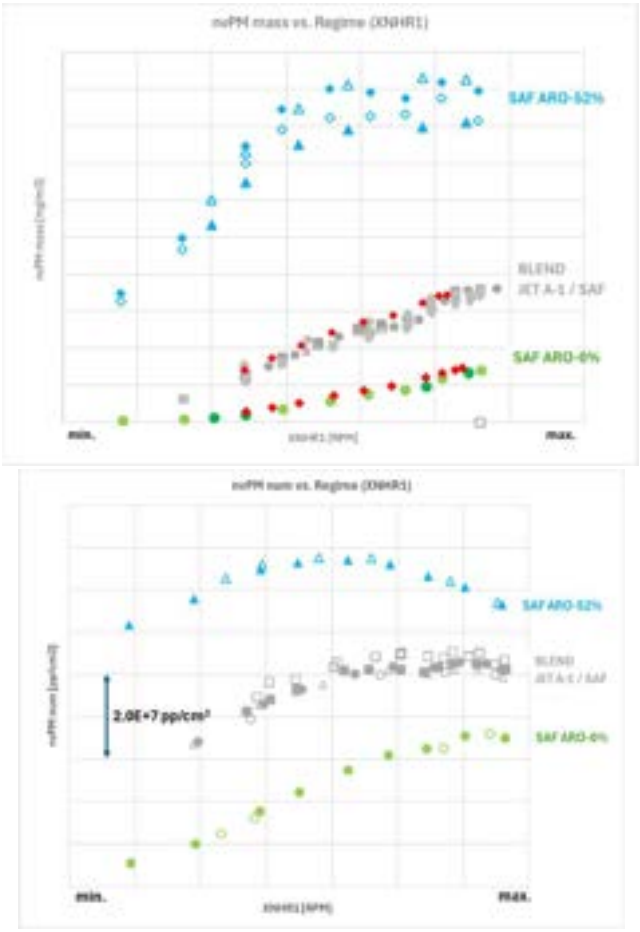


Figure 2: *Evolution of nvPM_mass (left) and nvPM number (right) vs. Engine Regime (red dots correspond to previous tests for reproducibility purposes)*

Lilienthal project: a Design-Build-Fly for Education and Applied Research

Emmanuel Bénard[1], Pierre-Alain Yvars[2], Antoine Lanthony[2], Yannick Pannier[3], Noureddine Guerrassi[4], Rémi Azouit[4], David Rodriguez Velasco[5], Jean-Baptiste Daramy[5], Maxime Liege[5], Maxime Tolu[5], Clément Pfiffer[1,*], Diego Martinez-Gonzalez[1], Sassine Sassine[1], Karnika Saklecha[1], Salome Marques-Pereira[1], Alexandra Nieto-Castillo[1], Hei Yui Wong[1], Hana Hana-Shahir[1], Praseeth Sharma[1], Sébastien Leroux[1], Nabile Lawali-Ali-Gado[1]

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1. Introduction / Objectives

As simulation has played a prominent role in education and research for decades, it is now essential to reintroduce a strong experimental component into the overall learning pathway of future engineers. This is particularly true of the aerospace sector, which is characterized by extremely complex architectures and is replete with critical functions. This is why, as has recently been re-examined at European level , modelled on the German Akafliegs, with a focus on fully interdisciplinary skills within a context identified by strict constraints regarding environmental impact, competitiveness and safety.

As part of a national effort, the PEGASE project, funded by the French National Research Agency (France 2030 plan) is a comprehensive and original training programme based on academic courses and comprising two innovative cross-disciplinary components: a portfolio of digital solutions and a project-based approach. All training activities will incorporate awareness-raising on environmental issues. Multi-level, multi-site learning is also at the heart of this initiative, with the development of low-carbon, electric platforms incorporating technological building blocks and emerging materials. The Lilienthal project brings together five institutions of the ISAE group, across the Occitanie and Nouvelle-Aquitaine regions in the South-West of France. It involves the development of two technology demonstrators (electric or even hybrid microlights) to demonstrate the potential of carbon-free aviation right through to its application in flight.

2. Methodology

The starting point of the project has been the selection of a low-power two-seater, of the French microlight category, with quite clean aerodynamics, and very light, as it was initially designed to be powered with an automotive diesel engine.

Other essential elements in the selection of the model were linked to the requirement of a well-documented design, a strong community of home builders for over 10 years, a wide variety of variants (engine and materials), and an overall moderate cost.



Fig 1: Selected microlight aircraft: the GazAile 2

Six work packages have been defined to tackle the following steps: Preliminary Design – Aircraft Pre-Project; Detailed Design of Subsystems Based on Preliminary Design and Existing Analysis; Environmental, Maintenance, and Certification Analysis and Validation; Manufacturing Environment and Fabrication. Those tasks are spread over the consortium, in relation to each institution profile. For example, ISAE-SUPAERO will hold responsibility for the manufacturing of the wing of the reference aircraft.

3. Results / Conclusions

This paper presents a new DBF project federating different French aeronautical universities. Apart from the purely educational aspect, a major opportunity is provided by Lilienthal confrontation with different innovative modifications of the original aircraft to be tested in full scale low speed demonstrator for research ideas.
Several research directions are already envisioned: electric and hybrid propulsion, bio-composites for non-critical components, optimized aerodynamics, flight controls.
We hope that this initiative will attract the interest of other universities in Europe, with a view to creating a network whose core aim is to introduce students to aspects of technology and testing, ideally right through to the flight stage.

A Hybrid 1-D/3-D Framework for the Design and Optimization of Ram-Air Ducted Thermal Management Systems in Electric Aircraft

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1.Introduction / Objectives

Fossil-fuel powered aviation has been the norm ever since the 1920's. In recent years, evidence has shown that commercial aviation contributes to about 3.5% of global carbon emissions . To tackle this issue and decarbonize the aviation sector, electric propulsion is considered as the forerunner for replacing fossil-fuel . Despite the many advantages of electric aircraft, they produce significant amounts of low-grade waste heat that must be dissipated to prevent component overheating (safety) and to maintain functionality of the power source (efficiency). Therefore, there is a strong need for a well-designed Thermal

Management System (TMS) that dissipates heat without impacting aerodynamic performance. A reliable and validated design tool for this purpose will considerably reduce development time in the design phase of such aircraft.

2.Methodology

The present work develops a comprehensive design methodology for a ram-air–based ducted thermal management system (TMS) tailored for electric aircraft. The framework is grounded in a physics-based one-dimensional (1-D) model that enables systematic sizing and performance evaluation of key components, including the propeller, the duct's diffuser, the heat exchanger, a potential puller fan, and the duct's nozzle. Within this model, the spatial evolution of primary state variables, namely pressure, velocity, and temperature, are captured to understand the coupled aero-thermodynamic behavior of the ram-air duct and its repercussions on the TMS performance. Building on the 1-D predictive model, a multi-objective optimization framework is implemented to explore the design space and identify optimal configurations. This approach helps derive key performance indicators (KPIs), with particular emphasis on aerodynamic cooling drag as a governing metric for system efficiency and integration penalty (see **Figure 32**).

Recognizing the inherent limitations of reduced-order modeling in capturing complex flow phenomena, particularly in regions with rapid area variation and strong streamline curvature, a high-fidelity three-dimensional (3-D) computational fluid dynamics (CFD) analysis is conducted to complement the 1-D results. The CFD study serves to quantify deviations between the 1-D predictions and resolved 3-D flow physics, providing a correctional delta that characterizes model fidelity. The combined 1-D/3-D methodology thus establishes a hierarchical design and validation framework, enabling both efficient system-level exploration and localized flow-accurate assessment of ram-air ducted TMS architectures for next-generation electric aircraft.

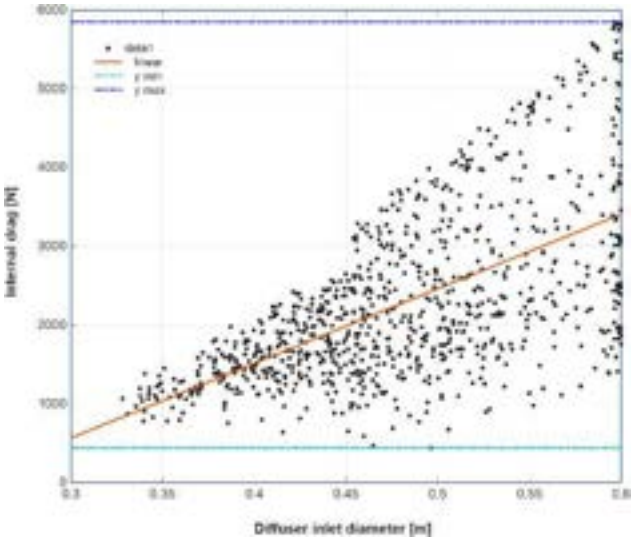


***Figure 32**: The figure illustrates the solution space of the optimization problem. Each point represents a viable TMS system (e.g., the system is capable of dissipating a given heat load. Here, the influence of the ram-air duct inlet area on the internal drag (KPI) is plotted. The optimum is observed to be around 0.325m of the diffuser inlet diameter.*

3.Results / Conclusions

In the current study, the TMS has been designed and evaluated for a hydrogen fuel-cell based electric aircraft, using the De Havilland Canada Dash 8 Q300 as a baseline case study. Our analyses reveal the design sensitivities to different duct geometry parameters, and their implication on the aerodynamic drag penalty. aFor the objective functions, two design points were considered i.e. cruise and take-off. From a system-level perspective, a more effective strategy seems to be to formulate the optimization problem with cruise drag minimization as the primary objective while enforcing take-off thermal performance as a hard constraint, rather than designing the TMS around take-off conditions, since this affects the cruise drag performance implying reduced aircraft range. In addition, the performance of the resultant best-performing configuration is investigated computationally through high-fidelity CFD and validated. This hybrid 1-D plus 3-D CFD approach enables the design of robust ram-air duct systems that achieve acceptable performance across all flight phases.

A Parametric Reduced-Order Model for Rapid Flight-Envelope Loads Prediction of a Flexible Aircraft

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1. Introduction / Objectives

Aircraft loads certification (EASA CS-25) requires the critical gust and manoeuvre loads to be identified across the entire flight envelope, for every mass and centre-of-gravity (CG) configuration. The classical "loads loop" evaluates hundreds to thousands of load cases —

many Interesting Quantities such as bending moments, shears and torques at numerous monitor stations, over families of gusts and manoeuvres, at many flight points — with a full-order aeroservoelastic model, and must be repeated at every design iteration. This work develops an automated Parametric Reduced-Order Model (PROM) that screens the full flight-and-mass envelope in near real time, driven by a commercial aeroelastic solver. Beyond prior PROM work it adds mass/CG (fuel and payload) as model parameters, a stability-preserving interpolation, and recovers correlated section loads along both wing and fuselage for rapid combined-load envelopes used in structural sizing.

2. Methodology

The aeroservoelastic plant is built once, offline, at a small number of sampling Mach numbers. A commercial aeroelastic solver (ZAERO) provides the unsteady generalized aerodynamic force (GAF) matrices for structural motion, gust and control-surface inputs (Q_hh, Q_hg, Q_hc) tabulated against reduced frequency. These are fitted by a pole-optimised extended Roger rational-function approximation and assembled, with the generalized mass and stiffness of a beam finite-element modal basis, into a linear time-invariant state-space full-order model (FOM). Each FOM is reduced by balanced truncation to a compact (~34-state) reduced-order model.

A parametric ROM is then constructed so that loads at any operating point are obtained with no new aerodynamic solve. Only the Mach axis requires interpolation of the reduced state-space matrices (a cubic, congruence-aligned scheme); altitude enters analytically through the dynamic pressure, and mass/CG enters through a fixed multi-model modal basis, in which a fuel or payload change re-projects only the generalized mass matrix while the aerodynamics are held fixed. Because element-wise interpolation does not guarantee stability, the interpolated plant is repaired by a pole-reflection step so every screened point is time-marchable.

At each flight-and-mass point the PROM is excited by a family of "1-cosine" discrete gusts spanning the regulatory gradient range and by elevator and aileron step manoeuvres. Internal section loads — axial, shear, bending and torque — are recovered along all wing and fuselage stations by the mode-displacement method, and pairs of correlated loads (bending versus torque) are wrapped by a convex hull to give the combined-load envelopes used for sizing. The complete workflow is implemented as a reusable, scripted orchestration layer around the commercial solver, so that a handful of full-order solves enables an effectively unlimited screening of the envelope. Accuracy is validated at flight points held out of the sampling set against the corresponding full-order solutions.

3. Results / Conclusions

The method was demonstrated on a free-flying transport-aircraft aeroservoelastic model. A 16-point Mach–altitude doghouse (Figure 2a) combined with fuel and payload variation was screened across gust and manoeuvre disciplines: 3600 load cases in about 80 s, after only four full-order solves. At a held-out flight point the PROM reproduces the full-order correlated wing-root load envelope to 0.04 % (Figure 2b), well within the ±3.5 % accuracy target, and the mass/CG re-projection recovers the configuration frequencies to better than 0.3 %. The screening speed-up grows with the number of points evaluated, exceeding two orders of magnitude for an envelope-scale sweep (Figure 2c). The PROM thus delivers full-envelope

wing and fuselage load envelopes at a fraction of the full-order cost, making rapid, repeatable loads screening practical within an industrial design loop on a commercial solver.

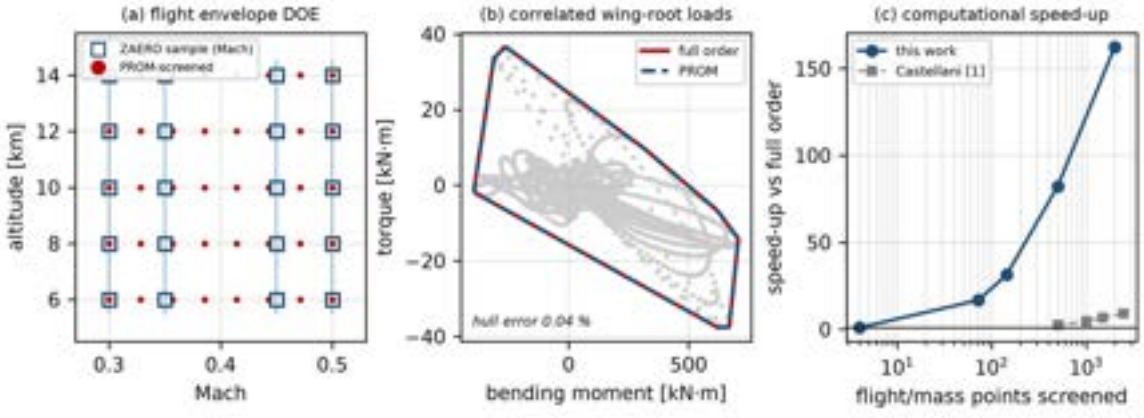


***Figure 2**. (a) Mach–altitude flight-envelope DOE — four sampled Mach numbers feed the full screened grid; (b) correlated wing-root bending–torque envelope, PROM versus full order at a held-out flight point; (c) computational speed-up versus the number of flight/mass points screened.*

Comparison of aluminum and POM projectile hypervelocity impact on Whipple Shield target

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1.Introduction

The ongoing development of composite materials in satellite structures leads to increasing number of polymerical debris navigating in LEO . A test performed at Eurenco Engineering have highlighted larger damages when impact by polymerical projectile in comparison with metal vs metal impact scenario. The observed phenomena could not only be explained by pure mechanical kinetic effects and may be the result of potential solid/gas phase change or chemical reaction of polymer elements leading to higher energy release.
The aim of this paper is to evaluate the effect of projectile material on debris cloud expansion, on the damage induced to a target in order to identify the source of the observed phenomena. An experimental configuration is therefore proposed comparing the damage induced by aluminum and polymeric material projectile at similar kinetic energy on single wall and Whipple shield aluminum targets at velocities up to 6 km/s.

2.Methodology

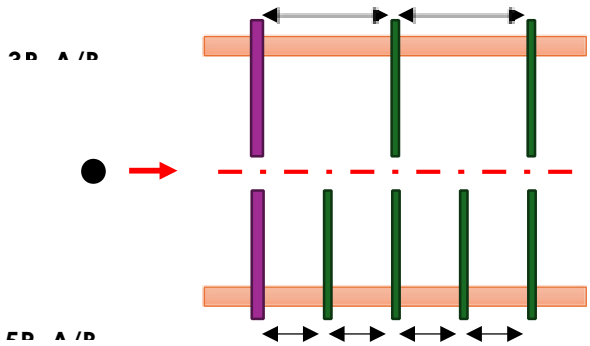


Figure 1. *Targets configuration.*

The testing configuration has been designed considering an equivalent energy impact for a given velocity by launching projectiles of similar mass resulting in a diameter of 3.2mm for aluminum (Al.) and 4.0mm for POM. As a consequence, the projected surface area is larger for the POM projectile. The target consists of multiple spaced aluminum plates (5785 grade except for 0.4mm thick that were in 6061T6) of different thicknesses (***Figure 1***). To study both the development of debris cloud generated by the impact and its effects on the target plate, two spacings distance of target plates are considered: target named as "3P" has three plates with 40mm spacing whereas "5P" target has five plates with 20mm spacing. For "XP-A" targets, a bumper of 1.5mm thick followed by 1.0mm plates are used whereas for "XP-B" the bumper is 1.0mm thick and the remaining plates have 0.4mm thickness. The impact event is monitored using both high speed camera and piezo-electric pressure.

3.Results / Conclusions

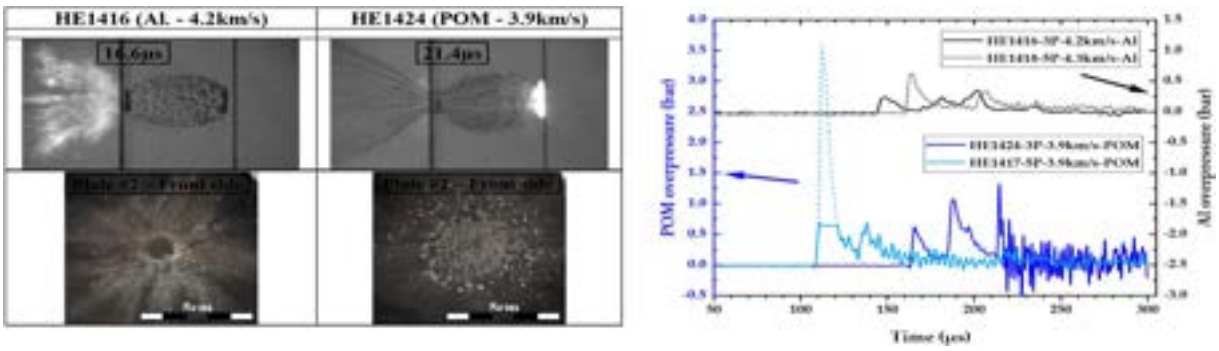


Figure 2. *Comparison of aluminum and POM projectile impact at 4km/s.*

Figure 2 shows the results from two impact tests at similar projectile velocity and energy with a Ø3.2mm Al. projectile used for HE1416 (left column) and a Ø4.0mm POM projectile for HE1424 (on the right).
The aluminum projectile generates more fragments of smaller size and an agglomeration of projectile debris on the front size. The aluminum sphere is shattered but not well dispersed. Due to this lower dispersion of fragments, a hole of Ø12.4mm diameter is present in the impact axis of the second plate with the aluminum projectile whereas only some few small perforations are observed with the POM. Interestingly, most of those few small holes are distant from the impact axis and therefore are associated to the aluminum fragments of the bumper plate. In both cases, the second plate undergoes a global deflection. In this configuration (impact velocity and target thickness), the aluminum projectile is more damaging for the target.
Regarding the impact overpressure, aluminum projectile generates lower overpressure (below 0.5bar) while it can reach up to 3.5bar for POM projectile. There are also multiple pics on most of the curves which may be due to the secondary impacts or some reflection of the initial wave. The shape of the first pic is very similar to that of the shock wave generated by explosives: sudden increase followed by exponential shaped like smooth relaxation.

Numerical assessment and validation of URANS predictions of shock-induced separation in an overexpanded thrust-optimized parabolic nozzle

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Tecnológico de Monterrey, Mexico

1. Introduction / Objectives

Shock-induced boundary-layer separation in overexpanded rocket nozzles governs side-load generation and constrains engine operation during start-up and shutdown. Its prediction is highly sensitive to numerical and turbulence-modelling choices, which are frequently reported without a systematic assessment. This work quantifies that sensitivity for an axisymmetric compressible URANS methodology applied to the DLR Lampoldshausen thrust-optimized parabolic nozzle (area ratio 30) and compares the predictions with published cold-flow nitrogen measurements. A convergence criterion based on the residual reduction within each physical time step is introduced as part of this assessment.

2. Methodology

Simulations are performed in SU2 with implicit dual-time stepping. Four grid levels spanning 5.9k to 86k cells are assessed, with near-wall resolution ranging from $y^+ \approx 60$ on the coarsest to y^+ of order unity on the finest, together with successively halved physical time steps. Beyond the usual grid and time-step study, convergence is monitored through the residual reduction

achieved within each individual physical time step.
Comparison with experiment is made at the nozzle pressure ratios for which the measurements report free shock separation; the restricted-shock-separation regime, whose onset is hysteresis-dependent, is left outside the scope of the present study. The wall-pressure comparison is reported both with and without the axial alignment uncertainty of the digitized contour, whose exact coordinates are not published.
Turbulence-model sensitivity is examined by comparing Menter SST and Spalart-Allmaras on identical grids, complemented by a cross-solver comparison of wall-pressure distributions computed with Eilmer 5 on the coarse mesh with a common turbulence model (Spalart-Allmaras), so that solver and turbulence-model effects are reported separately. Finally, an extended time record is used to characterize the separation-shock motion against the measured wall-pressure spectra.

Figure 1. *Instantaneous Mach-number field computed with Eilmer 5 (Wilcox k-ω) on the coarse mesh at t = 3.00 ms and nozzle pressure ratio 50, a numerical assessment case outside the experimentally measured range. The dashed line marks the first wall location with reversed flow.*

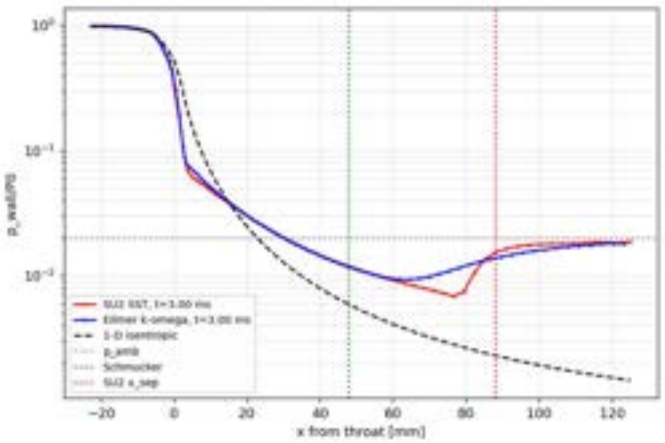


Figure 2. *Wall-pressure distributions at nozzle pressure ratio 50 and t = 3.00 ms from SU2 (Menter SST) and Eilmer 5 (Wilcox k-ω) on the same coarse mesh, with the 1-D isentropic solution, ambient pressure, the Schmucker criterion and the SU2 separation location for reference. Preliminary; different turbulence models.*

3. Results / Conclusions

The per-time-step convergence criterion proved necessary: simulations can remain numerically stable while under-converging their inner iterations, resolving each time step poorly and shifting the predicted separation location. Steady RANS failed to converge with two independent solvers, motivating the unsteady treatment. As a first code-to-code check

at a nozzle pressure ratio of 50, outside the measured range (Fig. 1), SU2 (Menter SST) and Eilmer (Wilcox k-ω) on the same coarse mesh predict separation locations 2.5 mm apart (2.9%) (Fig. 2). The full contribution will report grid- and time-step-converged wall-pressure distributions and separation locations against experiment, their sensitivity to turbulence model and solver, and the characterization of separation-shock motion. Together, these results identify which numerical choices must be reported for URANS predictions of nozzle flow separation to be reproducible.

Aerodynamic Fan Design and Trade-Offs for Propulsion Systems with Integrated Heat Exchangers

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1. Introduction

The integration of heat exchangers within the flowpath of electrically driven fans challenges several long-established assumptions in fan design. Conventional single-stage fans are typically designed with fan-face Mach numbers around 0.6-0.65 [1], whereas efficient heat exchanger operation favours in significantly lower Mach levels (0.1-0.2) [2]. Bridging this mismatch generally requires high levels of diffusion between these components, resulting in substantial pressure losses and reduced system efficiency. This raises a fundamental question: should fans intended for integrated heat-exchanger propulsion systems be designed differently from conventional aircraft fans? To address this question, the present work investigates the aerodynamic and system-level implications of low-Mach fan designs for integrated fan-heat exchanger propulsion architectures.

2. Methodology

The preliminary aerodynamic design is performed using the DLR in-house 2D throughflow design tool coupled with an optimization framework [3]. A series of optimization studies is conducted to investigate the aerodynamic implications of designing a ducted e-fan for low fan-face Mach numbers ranging from 0.3 to 0.6. The optimization framework adjusts key fan design parameters, including flowpath geometry (hub and tip lines), rotational speed, and blade-row characteristics, to satisfy the performance requirements derived from the cycle design while maintaining acceptable levels of aerodynamic efficiency.
Subsequently, the fan-face Mach number is fixed and the potential to diffuse the flow within the fan stage is investigated through a second optimization campaign. The resulting trade-off between maximizing fan-stage efficiency and maximizing flow diffusion is used to assess how diffusion can be distributed within the propulsion system. The Pareto-optimal solutions provide design guidelines for fan stages integrated with downstream heat exchangers and quantify the extent to which diffusion can be shifted from dedicated duct diffusers into the fan stage itself, thereby reducing the need for complex intermediate diffuser concepts.

3. Results / Conclusions

The results show that fan optimisation for integrated heat-exchanger propulsion systems

differs significantly from conventional fan design. While lower fan-face Mach numbers can improve fan-stage efficiency due to the interplay between shock losses and profile losses, the optimum system-level performance is obtained at a fan-face Mach number of approximately 0.50 due to the trade-off between intake and diffuser losses. Increasing diffusion within the fan stage reduces stator outlet Mach number and decreases downstream pressure losses, leading to an improvement in installed efficiency of approximately 2% [4]. The study demonstrates that low-Mach fan design is a key enabler of integrated fan–heat exchanger propulsion architectures and should be considered early in the design process.

Competency Based Training for Greener Aerospace Special Processes through Citric Acid Passivation of Stainless Steel

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1. Introduction / Objectives

The transition to greener aerospace chemical processing requires technicians who understand surface chemistry, execute approved instructions and evaluate environmental performance without compromising conformity. Citric acid passivation provides a relevant training case, although its technical and environmental benefits depend on alloy characteristics and treatment conditions. Building on earlier learning-outcome-based training in green aerospace chemical processes using drag-out as a teaching case, this work develops a process-specific course for aerospace technicians, translating passivation science, process control and resource efficiency into observable professional competences. Its objective is to connect scientific principles with workshop activities, assessment evidence and practical calculations. The contribution is a reproducible educational framework supporting the responsible adoption of greener special processes, rather than a new passivation chemistry or a claim of production qualification.

2. Methodology

A documentary curriculum-design approach combines aerospace passivation evidence, the drag-out training approach, learning-outcome guidance and the scope of ASTM A967/A967M-25. Technician tasks are decomposed into applicability checks, surface preparation, bath control, rinsing and drying, verification, traceability and environmental comparison. Each task is linked to an observable learning outcome and an assessment evidence item. The proposed 24-hour course comprises six modules, including twelve hours of practical activities and assessment.

The scientific component explains the removal of iron contamination through citrate complexation and the role of the chromium-rich passive surface film. Concentration, temperature, treatment time, alloy condition and recontamination are addressed as interacting process variables. A supervised workshop exercise uses identified non-flight coupons, an approved educational instruction, calibrated equipment and assigned acceptance checks. Related studies on stainless steel 304 surface functionalisation and protective coatings [5,6] provide complementary examples linking surface chemistry, wettability and corrosion assessment, helping trainees distinguish passivation from coating-

based protection.
A six-dimension assessment rubric combines direct observation, batch records, interpretation of verification results and calculation tasks. The proposed pass rule requires satisfactory performance in every dimension and no critical error. Unauthorised process changes or release without required acceptance evidence cannot be compensated by higher scores elsewhere.
Mass-balance models determine reagent and water quantities from target solution mass, active-acid mass fraction and reagent assay. A further model calculates authorised reagent addition to an under-concentrated bath while accounting for the increased final mass. Drawing on the process-bath and rinse-bath analysis in the drag-out course [2], calculation activities also address solution carry-over into rinsing and its implications for chemical loss and rinse-water demand. Resource intensity is evaluated per accepted output, including rework within a common comparison boundary. Worked examples explicitly state assumptions and units and are distinguished from qualified production recipes. The proposed validation protocol includes independent technical and pedagogical review, pilot delivery, delayed practical assessment and evaluation of assessor agreement.

3. Results / Conclusions

The design yields a modular curriculum, a practical assessment rubric and a calculation framework connecting surface science with technician decisions. An illustrative mass balance requires 0.2020 kg of reagent with 99.0% active-acid assay to prepare 5.000 kg of solution at 4.0% active-acid mass fraction; this is an arithmetic example, not a qualified bath recipe. Environmental comparison incorporates accepted output and rework, preventing misleading conclusions based solely on resource consumption per batch. The framework extends the earlier drag-out teaching case [2] to citric acid passivation by integrating process-specific acceptance evidence and a critical-error assessment rule. The principal conclusion is that greener-process training should integrate chemical understanding, controlled execution and quality-conditioned environmental reasoning. The course has not yet been delivered or externally validated. No measured learning improvement, environmental saving or process qualification is claimed. The framework provides a reproducible basis for subsequent review and pilot implementation.