Multidisciplinary optimization as an enabling tool for designing sustainable aircraft

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Introduction

- Air travel has been continuously growing in the past decades at an accelerated pace (**doubling every 15 years**) mainly impelled by the growth of the Gross Domestic Product (GDP), global trade and average income.
- Although the Covid-19 pandemic severely impacted commercial aviation experts predict that this sector **will continuously grow** and resume to pre-pandemic values.

References: ICAO https://www.icao.int/annual-report-2014/Pages/the-world-of-air-transport-in-2014.aspx
IATA, https://www.iata.org/en/iata-repository/publications/economic-reports/air-passenger-market-analysis---june-2023/

Introduction

- Linked to this evolution is the concerning **growth of both pollutant and noise emissions** with prejudicial consequences for the well-being of both humans and ecosystems, even though technological improvements have allowed for reductions of these emissions.
- These technological improvements, mainly in the propulsive system, have allowed for **reductions up to 80% and 75%** in terms of fuel burn and noise emissions, respectively, when compared to the early commercial aviation days.

References: F. Yin and A.G. Rao, "A review of gas turbine with inter-stage turbine", *Progress in Aerospace Sciences*, Vol. 121, 100695, 2020, https://doi.org/10.1016/j.paerosci.2020.100695

Introduction

- According to Lee et al. (2021), aviation industry is responsible for only **3.5% of the anthropogenic climate changes** with non-CO_2 related emissions, namely contrails, presenting a similar impact to the CO_2 related ones.
- Despite this value being smaller than other means of transportation, the energy required to transport a person in the same distance is larger.

Transportation Vehicles	MJ/(PAX.km)
Buses	0.15 - 0.49
Electric and Hybrid Cars	0.31 - 0.45
High Speed Trains	0.35 - 0.64
Diesel Cars	0.65 - 1.05
Petrol Cars	0.79 - 1.6
Aircraft	1.11 - 1.62

- Thus, pressing this industry to find energy and cost efficient solutions.

References: D.S. Lee, et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018", *Atmospheric Environment*, Vol. 244, 117834, 2021, https://doi.org/10.1016/j.atmosenv.2020.117834
J.-H. Zheng, et al., "A universal mass-based index defining energy efficiency of different modes of passenger transport", *International Journal of Lightweight Materials and Manufacture*, Vol. 4, No. 4, pp. 423-433, 2021, https://doi.org/10.1016/j.ijlmm.2021.06.004

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- To address this urgent issue, governmental institutions have launched documents such as the Flightpath 2050 by the European Commission (EC) that set targets for the next generation of air vehicles.
- The 3 most demanding ones, in regard to the year 2000, are the following:
  - **75% in CO_2**;
  - **90% in NOx**;
  - **65% in perceived noise level**.
- However, these documents are currently being revised (e.g., European Green Deal by the EC), especially in what concerns pollutant emissions, to accelerate the introduction of more sustainable energy systems.

Reference: https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf

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- It is worth to mention that **these targets are sometimes conflicting**.
- For instance, by **reducing NOx emissions to improve the air quality, CO_2 emissions are likely to increase** (since the combustion is set to occur at a lower temperature), which lead to a higher impact on climate changes.
- Thus, **a good balance between these conflicting goals should attained**.
- According to Gobler et al. (2019) study, using their combined metric, NOx is responsible for 58% of the global impact on climate and air quality, while CO_2 only accounts for 25% and contrails 14%.
- Recent studies from Lee et al. (2021) report that contrails present a large impact to global warming and should be carefully considered.

References: Grobler et al., "Marginal climate and air quality costs of aviation emissions", *Environmental Research Letters*, 14, 114031, 2019, https://doi.org/10.1088/1748-9326/ab4942
D.S. Lee, et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018", *Atmospheric Environment*, Vol. 244, 117834, 2021, https://doi.org/10.1016/j.atmosenv.2020.117834

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- Thus, improvements across the main aircraft disciplines that can lead to more energy efficient designs are sought as well as novel aircraft configurations, always keeping in mind their environmental impact.
- However, these improvements at the discipline level can be prejudicial in light of others disciplines.
- Furthermore, unconventional configurations require an in-depth knowledge about their disciplinary behavior and especially their airworthiness, which usually takes a substantial maturation time.
- Therefore, on one hand, **Multidisciplinary Design Optimization (MDO)** tools are essential to achieve a fully optimized design that accounts for the main aircraft disciplines.
- On the other hand, **Unmanned Aerial Vehicles (UAVs)** can be seen as important testbeds to gain knowledge about novel features and prove their airworthiness.

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- In the next sections are presented my efforts towards a more sustainable aviation in terms of solutions that involve changes in the aerodynamic shape, propulsion, and energy source.
- These efforts are intertwined with other disciplines for solutions such as novel configurations and morphing systems, for which **MDO** was used.
- **UAVs** were developed to study and test some unconventional features, such flexible wings.
- To assess the environmental impact of different energy solutions, **Life Cycle Assessment (LCA)** was integrated right at the conceptual design stage.

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High Aspect-Ratio Wings

- Designing wings with higher aspect-ratio is a trend clearly visible in the most recent commercial airplanes.
- This is because it allows for **reducing the lift induced drag** and thus has the **potential to reduce fuel consumption (≈10%)**.
- However, associated to slender designs are **some structural and aeroelastic issues**.
- The former arises due to the higher root bending moments that leads to a mass increase, while the latter is caused by the higher flexibility that may lead to the occurrence of undesired phenomena (e.g. flutter).
- Therefore, to further explore potential fuel savings that may arise due to higher wing aspect-ratios **aerodynamics and structures should be couple**d.
- Furthermore, these undesired aeroelastic phenomena should be explored right from the early conceptual design phase to prevent expensive redesigns later in the process using adequate **Fluid-Structure Interaction (FSI)** frameworks.

Reference: **F. Afonso**, J. Vale, É. Oliveira, F. Lau and A. Suleman, "A review on the non-linear aeroelasticity of high aspect-ratio wings", *Progress in Aerospace Sciences*, Vol. 89, pp. 40-57, 2017, http://dx.doi.org/10.1016/j.paerosci.2016.12.004

Strut-Braced-Wing

- Strut-Braced-Wing (SBW) is another novel configuration that aims to **reduce the induced drag by increasing the wing aspect-ratio**.
- To minimize the structural mass increase a **strut is added to the main wing, causing additional drag**.
- Like for high aspect-ratio wings, flexibility effects should be accounted for at the early design stages.
- To better assess the eventual **aerodynamic benefits, high fidelity simulations should be included**.
- Therefore, **a MDO architecture needs to account for both wing flexibility effects and high fidelity simulations**.

Reference: M. Sohst, J. Vale, **F. Afonso** and A. Suleman, "Optimization and comparison of SBW and HARW aircraft configurations including non-linear aeroelastic effects", *Aerospace Science and Technology*, Vol. 124, 107531, 2022, https://doi.org/10.1016/j.ast.2022.107531

MDO Architecture

- Despite the advances in computational processing capabilities, **the simulation time of high fidelity calculations is still the major hurdle** to MDO.
- To accelerate the process, **Surrogate-Based Optimization (SBO)** can be employed.
- This is predicted to become a reality in aircraft design with the massive usage of **Machine Learning (ML)**.

Reference: M. Sohst, J. Vale, **F. Afonso** and A. Suleman, "Optimization and comparison of SBW and HARW aircraft configurations including non-linear aeroelastic effects", *Aerospace Science and Technology*, Vol. 124, 107531, 2022, https://doi.org/10.1016/j.ast.2022.107531

Blended Wing Body

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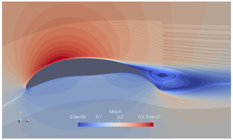
- A similar multidisciplinary design approach is needed for the Blended Wing Body (BWB) configuration.
- This designs aims to maximize aerodynamic efficiency by **seamlessly integrating the passengers inside the main wing**.
- Consequently, it **offers larger aerodynamic drag reductions ($\approx$ 25%)**.
- However, ensuring **stability and controllability becomes more complex**.
- Furthermore, the passenger comfort on the outboard wing part is lower.
- Nevertheless, BWB is seen as **good candidate for hydrogen powered aircraft** if the bulky tanks are stored in the outboard wing part.

Reference: **F. Afonso**, et al., "Strategies towards a more sustainable aviation: a systematic review", *Progress in Aerospace Sciences*, Vol. 137, 100878, 2023, https://doi.org/10.1016/j.paerosci.2022.100878

Morphing Solutions

- Fixed **wingtips** have allowed for fuel consumption reductions between **5% and 10% during cruise**.
- Enabling these devices with morphing capability can **improve off-design operations and maneuverability or even alleviate gust loads**.
- **Camber morphing** can also be used to **ameliorate performance in off-design conditions**, **while reducing noise during landing** by replacing conventional high-lift devices.



- **Flow control** is another to reduce drag **(up to** 45%**)** by keeping laminar a large flow portion.
- The main drawback of morphing solutions is the **added weight and complexity** of the mechanical systems.

Reference: R. Valldosera Martinez, **F. Afonso** and F. Lau, "Aerodynamic Shape Optimisation of a Camber Morphing Airfoil and Noise Estimation", *Aerospace*, Vol. 9, No. 1, 43, 2022, https://doi.org/10.3390/aerospace9010043

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All-electric Propulsion

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- Flying only with electric propulsion is one of the main goals of aviation **since there is no direct emissions in the use phase**.
- Furthermore, electric motors are **more efficient, simpler and cost less to maintain**.
- However, the source of electric energy to be integrated in an aircraft is still the main shortcoming of all-electric aircraft since current battery technology has a **substantially lower specific energy** when compared to fossil fuels (around 2 order of magnitude).
- Moreover, the **heat produced** by high power electric components is also another **important concern, requiring a more elaborate thermal management system**.

References: **F. Afonso**, et al., "Strategies towards a more sustainable aviation: a systematic review", *Progress in Aerospace Sciences*, Vol. 137, 100878, 2023, https://doi.org/10.1016/j.paerosci.2022.100878
M. Coutinho, et al., "A review of the recent developments on thermal management systems for hybrid-electric aircraft", *Applied Thermal Engineering*, Vol. 227, 120427, 2023, https://doi.org/10.1016/j.applthermaleng.2023.120427

Hybrid-electric Propulsion

- Thus, today only small aircraft with low energy and power demands are suitable candidates to be all-electric, such as those of **general aviation** and the envisioned **urban air mobility** segment or **solar powered concepts**.
- Solutions such as **hybrid-electric propulsion systems and/or hydrogen powered engines** (both hydrogen fueled combustion and fuel cells) are seen as **long-term possibilities**, while **sustainable aviation fuels (SAFs)**, such as biofuels or synthetic fuels, are considered as **mid-term solutions** once the **biomass is obtained from a sustainable source and not competing with food supplies**.

Reference: **F. Afonso**, et al., "Strategies towards a more sustainable aviation: a systematic review", *Progress in Aerospace Sciences*, Vol. 137, 100878, 2023, https://doi.org/10.1016/j.paerosci.2022.100878

Thermal Management Systems

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- All-electric, hybrid-electric and hydrogen powered aircraft need a suitable **Thermal Management System (TMS)** that can cope with the heat loads generated during flight.
- The heat loads in electric machines are **more difficult to dissipat**e than in combustion engines which expel heat for the exhaust.
- **Crygonic** requirements for hydrogen combustion has posed a substantial thermal management challenge.
- Thus, the propulsive system should be designing alongside the TMS to explore synergies.

References: M. Coutinho, et al., "A review of the recent developments on thermal management systems for hybrid-electric aircraft", *Applied Thermal Engineering*, Vol. 227, 120427, 2023, https://doi.org/10.1016/j.applthermaleng.2023.120427
I. Figueiras, M. Coutinho, **F. Afonso**, and A. Suleman, "On the Study of Thermal-Propulsive Systems for Regional Aircraft", *Aerospace*, Vol. 10, No. 2, 113, 2023, https://doi.org/10.3390/aerospace10020113
M. Coutinho, **F. Afonso**, A. Souza, D. Bento, R. Gandolfi, F. R. Barbosa, F. Lau, and A. Suleman, "A study on thermal management systems for hybrid-electric aircraft", *Aerospace*, Vol. 10, No. 9, 745, 2023, https://doi.org/10.3390/aerospace10090745

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Lithium-based Batteries

- The most promising batteries for all-electric or hybrid-electric systems are lithium-based, namely **Li-ion and Li-S**.
- The former type is already **widely available in the automotive industry**, while the latter one is being tested on the next generation of electric cars.
- Given their low energy densities when compared to kerosene, these batteries can only be used on hybrid systems for commercial aviation or in all-electric UAM aircraft.
- To thoroughly assess the environmental impact a **LCA** needs to be carried out.
- Even though the **LCA results evidenced substantial reductions in CO_2 emissions for the aircraft entire operational life**, for long range flights **reductions in the number of passengers and the range were needed**.
- Furthermore, these reductions in CO_2 emissions are **only possible if renewable energy sources are used to recharge batteries**.

References: J. Ribeiro, **F. Afonso**, I. Ribeiro, B. Ferreira, H. Policarpo, P. Peças and F. Lau, "Environmental assessment of hybrid-electric propulsion in conceptual aircraft design", *Journal of Cleaner Production*, Vol. 247, 2020, https://doi.org/10.1016/j.jclepro.2019.119477
F. Afonso, A. Ferreira, I. Ribeiro, F. Lau and A. Suleman, "On the Design of Environmentally Sustainable Aircraft for Urban Air Mobility", *Transport Research Part D: Transport and Environment*, Vol. 91, 102688, 2021, https://doi.org/10.1016/j.trd.2020.102688

Sustainable Aviation Fuels

- The usage of **Sustainable Aviation Fuels (SAFs)**, such as biofuels, is seen as an interesting mid-term solution for a more sustainable aviation.
- This is mainly because of two reasons:
  - **very small or no modifications are required** to current aircraft;
  - **CO_2 emissions in the production phase can decrease substantially**.
- However, currently the availability of **sustainable biomass to produce biofuels is very low** besides the higher market price than kerosene.
- An alternative under consideration is the usage of **SAFs** that can be **synthetically produced in combination with a carbon capturing and renewable energy systems**.

Reference: **F. Afonso**, A. Ferreira, I. Ribeiro, F. Lau and A. Suleman, "On the Design of Environmentally Sustainable Aircraft for Urban Air Mobility", *Transport Research Part D: Transport and Environment*, Vol. 91, 102688, 2021, https://doi.org/10.1016/j.trd.2020.102688

Hydrogen-based Fuel Cells

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- For a VTOL UAM aircraft the propulsive system can be developed to run on both **batteries and fuel cells**.
- The latter can be sized for cruise since these operate better at constant power, while the former can provide the extra power needed for VTOL operations.
- Despite **hydrogen-based fuel cells present higher specific energy densities than batteries**, these devices require **hydrogen supply which occupies a large volume**.
- Furthermore, **the production of "green hydrogen" and its supply chain is currently very small**.
- When comparing with all-electric systems, the hydrogen-based fuel cells despite presenting a **lower global warming potential** their impact to **resources consumption is larger**.
- Regarding the human health category, it is not clear if fuel cells present a lower impact than batteries.

Reference: J. Fernandes, "Aircraft Lifecycle Analysis for Urban Air Mobility using Batteries and Fuel Cells", M.Sc. Thesis, IST, Universidade de Lisboa, Portugal, 2021

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Concluding Remarks

- Clearly the potential of **MDO** towards a more sustainable aviation can be observed from the work presented, either by reducing emissions, increasing performance or mitigating noise.
- However, computationally it is still expensive to use **MDO** when high fidelity models are employed.
- **UAVs** are essential testbeds for studying not only unconventional design features in-flight, but also the airworthiness of concepts coming out of the **MDO** process.
- Despite **UAVs** can provide useful insights that help to prevent expensive late design changes, some conditions can only be studied with an expensive full size prototyping.
- **LCA** at the early aircraft design stages changes is very helpful since it can be used to exclude solutions based on their environmental impact.
- Nevertheless, the impact associated to the airframe and its manufacturing process is very coarse to provide a good estimation, especially for novel configurations, at the these early design stages.

Acknowledgments

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