GLOWOPT – A NEW APPROACH TOWARDS GLOBAL-WARMING-OPTIMIZED AIRCRAFT DESIGN

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ABSTRACT:
A new concept for designing aircraft with minimum climate impact is presented. The paper describes the GLOWOPT approach, which is currently being implemented in the framework of the Clean Sky 2 programme. It aims at developing and validating so-called Climate Functions for Aircraft Design (CFAD). Those functions constitute an easy-to-use tool, which can be integrated into existing aircraft synthesis workflows without high adaptation effort. They will be made available to the relevant stakeholders including aircraft manufacturers, and thus allow for the development of new aircraft with a significantly reduced impact on global warming.

1. INTRODUCTION

The impressive growth rate of the aviation sector deems the aviation emissions at high altitude highly relevant. Besides CO_2 emissions, in particular non-CO_2 emissions have a significant impact on the climate. In Europe, the main findings of the IPCC (1999) report estimated the magnitude of the non-CO_2 Radiative Forcing (RF), metric to quantify climate impact, to be 63% of the total RF from aviation in 1992 [1]. These non-CO_2 effects, stemming, e.g., from NO_x emissions and contrail formation, are largely independent from CO_2 emissions, and their climate impact depends on the current atmospheric state and background concentrations. Therefore, the effect of non-CO_2 emissions on climate is dependent on time and locus (latitude, longitude and altitude) of emissions. Emissions of NO_x, for example, result in formation of tropospheric Ozone (O_3) and decrease the concentration of ambient methane (CH_4) leading to a positive RF. Contrails may form through the mixing of the hot and humid exhaust plume with the sufficiently cold ambient air, and can persist for hours if the air is supersaturated with respect to ice becoming so-called contrail-cirrus. This aviation-induced cloudiness can have either a positive or negative RF depending on the optical properties and the angle of incidence of the sun, but overall, causes a positive RF [2]. The overall climate impact from aviation emissions estimated by past studies is shown in figure 1.

The interest in aviation impacts on climate change has led to the initiation of a number of projects, such as CATS, WeCare, REACT4C or ATM4E, for finding measures to reduce the climate impact of aviation. These projects both addressed technological measures, including changing the aircraft design, and operational measures, like e.g. climate-optimized flight planning. The projects CATS (Climate-compatible Air Transport System) and WeCare (Utilizing Weather information for Climate efficient and eco-efficient future aviation) were carried out by DLR. Within CATS a multi-disciplinary simulation and analysis approach to

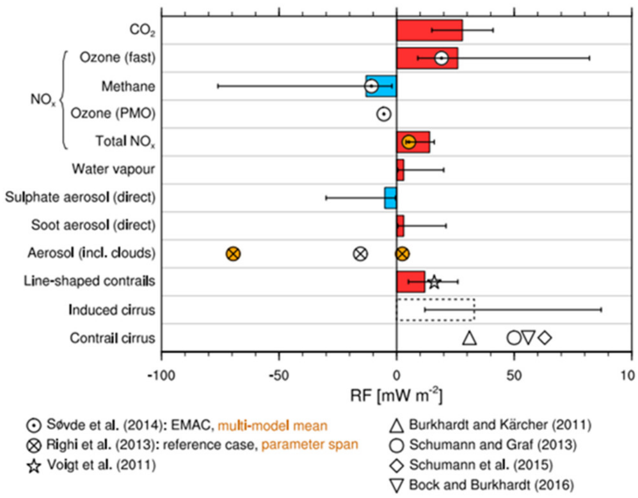

Figure 1: Overall climate impact of aviation emissions. [4]

study the climate impact of aviation with respect to changes in the operating conditions as well as the aircraft design parameters was established. It was found that replacing the entire A330-200 fleet by an aircraft redesigned for a cruise Mach number of 0.72 and an initial cruise altitude of 8000 m could reduce the climate impact by 32% without any increase of cash operating cost [3]. In WeCare different strategic and tactical measures were analyzed, including the introduction of a strut-braced wing aircraft with an open rotor engine, the application of Intermediate Stop Operations on long-haul routes or the closing of air spaces, which are very climate-sensitive [4]. In the EU FP7 project REACT4C (Reducing Emissions from Aviation by Changing Trajectories for the benefit of Climate) a complex simulation framework was set up to optimize air traffic flow with respect to its climate impact. Here, the concept of climate cost functions (CCF) for trajectory optimization was introduced for the first time and calculated for five representative days for winter and three days for summer. Those CCFs were used to optimize flights between Europe and North America with respect to their climate impact [5]. The SESAR2020 Exploratory Research project ATM4E (Air Traffic Management for Environment) extended the concept of CCFs even further to algorithmic CCFs (aCCFs). ACCFs are a simple mathematical means to calculate the climate cost of a unit emission at a certain location and time based on a small number of atmospheric parameters. This allows the real-time computation of the climate impact and therefore enables its consideration in flight planning [6].

Environmental targets have been formulated, e.g. by ACARE, to urge aircraft manufacturers and airlines to change the way aircraft are designed and operated [7]. A plethora of technologies are under investigation within the European research programme Clean Sky 2 aiming to develop innovative next generation green aircraft. In this context, the project "Global-warming-optimized aircraft design" (GLOWOPT) started in 2019 with the clear objective to develop a new instrument, which can be used by aircraft designers in combination with conventional aircraft design synthesis or Multidisciplinary Design Optimization (MDO) methods, in order to create new aircraft designs that have a reduced impact on climate.

In aircraft design optimization studies usually fuel burnt, maximum take-off mass or operating costs are used as objective functions. However, DLR's project CATS (see above), and studies by Vos et al. [8], Egelhofer [9] and Schwartz-Dallara et al. [10] already demonstrated that there is significant potential for reducing the climate impact of aviation, if aircraft are optimized for minimum climate impact instead, at comparably low additional costs. However, evaluating the effect of non-CO_2 emissions introduces complex climate-chemistry models into the multi-disciplinary optimization process. This requires a multitude of climate impact evaluations and increases computational efforts. The GLOWOPT project is set directly to enable such MDO process by developing Climate Functions for Aircraft Design (CFAD) that allow for the minimization of the climate impact of next generation aircraft without the need for an integrated climate impact assessment during the MDO process.

2. METHODOLOGY

Currently, in the aircraft design process the objective is to minimize operating costs on standard design missions while fulfilling certain Top Level Aircraft Requirements (TLARs) and satisfy further design constraints. The aircraft's environmental performance on fleet level is so far completely decoupled from that process as it, requires (1) in-depth knowledge on potential markets, route networks and typical operating conditions as well as (2) large expertise on emission modelling and atmospheric science.

The overall GLOWOPT concept is based on the idea that for a given market segment a climate optimized aircraft can be synthesized that can serve a statistically relevant aircraft fleet by minimizing a relevant climate function. This implies that climate models, route network models and aircraft design tools need to be employed in order to substantiate the design and operation parameters of such a climate optimized aircraft. An automated design framework will be utilized in order to perform the design and optimization tasks. By combining the route network study, the development of climate functions and the aircraft design synthesis methods, a multi-disciplinary optimization study of the aircraft/engine design parameters (payload, range, cruise Mach number and altitude, etc.) will be performed based on various cost functions. Based on this, an estimation of the mitigation potential by deviating from current typical operational parameters and current aircraft can be substantiated. A schematic representation of the proposed research methodology is shown in figure 2.

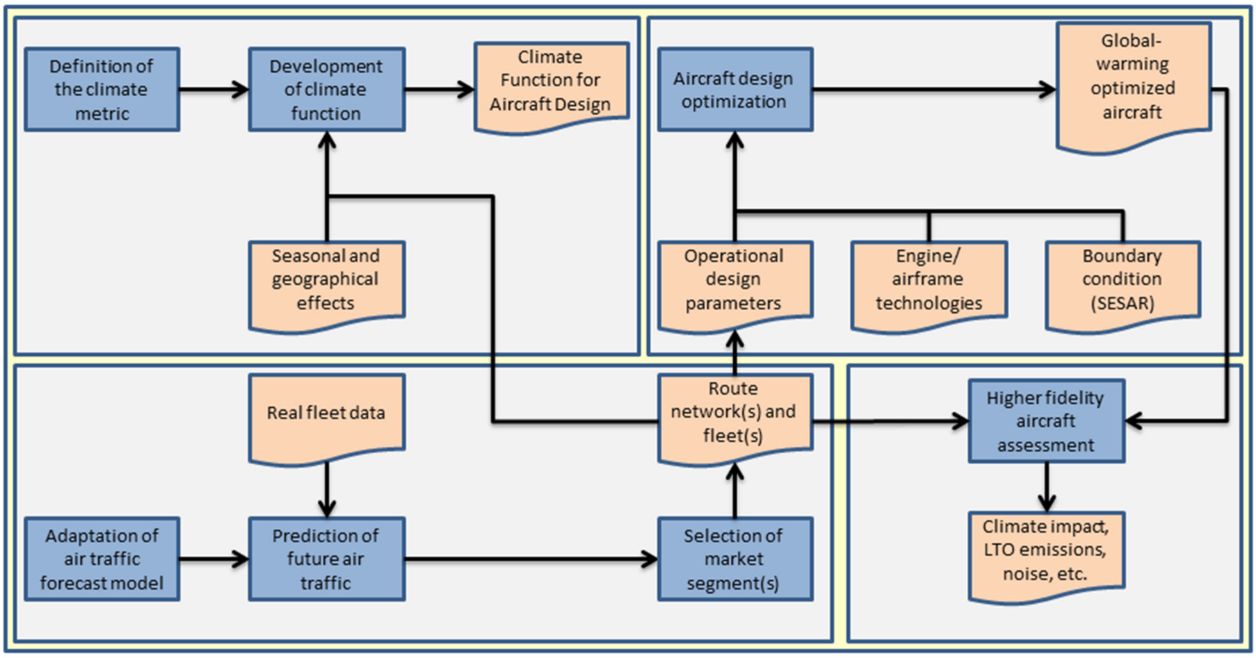

Figure 2: Interaction of different disciplines in the GLOWOPT approach

The GLOWOPT approach employs a common interface between the climate model and the aircraft design tool from addressing the global route network. The development strategy of the climate model will already include the information on global route network of the selected market segment. Additionally, the operational envelope of the climate optimized aircraft is determined by analyzing the worldwide fleet and route structure. With a forecast model the future air traffic flows can be predicted and utilized for identifying the TLARs for future years.

2.1 Climate Functions for Aircraft Design (CFAD)

Climate Cost Functions (CCF), sometimes also referred to as Climate Change Functions, represent mathematical objective functions to be used in single- or multi-objective optimization processes. 3-dimensional (latitude, longitude, altitude) CCFs can be used to determine the optimum route or trajectory of an aircraft, as they allow for the computation of the climate impact of a unit emission of the relevant species (CO2, H2O, NOx), which is released at a specific location. Assuming linearity this is simply scaled by the amount of emissions of the particular species. For the contrail effects the flight distance flown through regions with a certain contrail formation probability is considered.
Those CCFs were computed by virtually releasing a normalized amount of emissions in discrete grid cells and simulating the reaction of the entire climate system over a period of 3 years using a complex climate-chemistry model, which includes sub-models for the calculation of atmospheric, physical and chemical processes and their interaction with the ocean and land surfaces. As a result, based on the selected metric, the climate impact caused by this unit emission at that location and time was determined and used to describe the climate cost function of that grid cell. The climate functions that will be developed within GLOWOPT will specifically address the aircraft design process and therefore will look substantially different compared to those CCFs used for flight planning and trajectory optimization.

For the first time, climate functions for aircraft design (CFAD) will describe in detail the climate impact of spatially varying emissions depending on the key parameters which are affected by aircraft design. These CFAD will utilize the knowledge from the state-of-the-art CCFs developed in REACT4C and ATM4E projects and enhance them further by implicitly including the effect of the global fleet route network.

The GLOWOPT-CFAD are novel as they contain fleet level information in an aggregated way. Hence, this concept and the applied methodology bear the potential of being transferred and extended to other technology areas, e.g. for the design of alternative fuels or the development of new engine combustion technologies, that aim at a climate impact reduction of aviation on fleet level. Moreover, guidance for selecting suitable climate

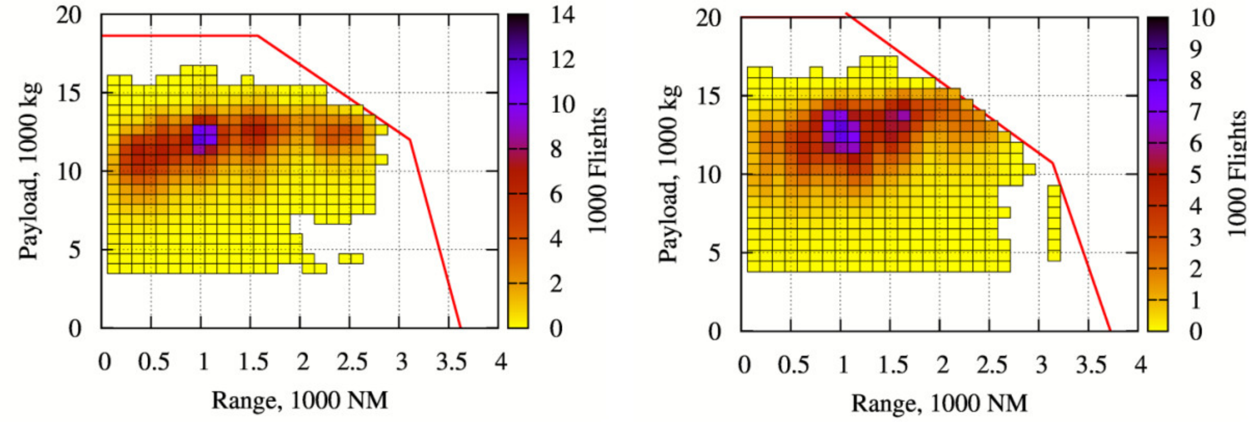

Figure 3: Annual number of flights and payload-range diagram of an Airbus A320-200 (left) and a Boeing 737-800 (right). [13]

metrics for this application is established based on the targets adopted from the Paris Agreement.

2.2 Representative Route Network and Fleet

The aircraft design process is based on a set of top-level aircraft requirement (TLAR) which define the design mission. The characteristic of any aircraft is usually represented by Payload-range diagrams. Each payload-range combination demonstrates the possible missions that can be flown by a specific aircraft. Airlines and other operators use these aircraft to make a profit, which implies that they will fly these aircraft on multiple routes at a combination of speed and altitude that maximizes their revenue. Also, to cater for network flexibility, most of the routes in the network have a mission range that is considerably below the maximum mission range (see Figure 3), which implies that the aircraft is actually oversized in terms of weight, wing area, and engine power to fly these missions. This results in unnecessary high emissions and global warming impact. The question is thus, for what top-level aircraft requirements (TLARs) the next generation of aircraft should be designed such that their impact on global warming is minimized while network flexibility is still ensured.

Therefore the GLOWOPT project specifically addresses the detailed analysis of the future aircraft fleet and route network. Range, payload, cruise altitude, cruise mach number, take-off and landing distance are the most important parameters required for the derivation of a new aircraft design. An overview of the required transport capacities on any flight segment, i.e. flight frequencies, aircraft size and passenger demand, in conjunction with technological and infrastructure constraints, e.g. airport related constraints, will constitute the basis for identifying the relevant TLARs and design constraints for the next generation climate optimized aircraft design.
For the analysis of the future global route structure, a model predicting the future aircraft movements will be applied. This model will be extended from an existing air traffic forecast model which consists of three network layers: (1) the passenger origin-destination demand network, (2) the routes network and (3) the aircraft movements' network [4]. The passenger air traffic demand and the aircraft movements network will be updated based on latest demand figures and will be extended to future global air traffic flows with a frequency-capacity model and fleet renewal model. Finally, a cluster analysis of the resulting air traffic forecast with respect to aircraft size and range as well as selection of aircraft market segment will be addressed for deriving the relevant design parameters and constraints.

Besides the TLARs, a representative route network for all selected market segments will be determined. These network routes will be used in the calculation of CFADs and for establishing an envelope of operational parameters. Additionally, climate impact along the representative route network will be estimated using AirClim modelling environment and will be compared against the resulting climate impact from GLOWOPT-CFADs for validation.

2.3 Climate Optimized Aircraft Design

In the past, studies have developed methodologies to include the climate change criteria into the preliminary design phase of the aircraft design [3, 9, 10]. Collectively, each of these comparative studies optimized the aircraft design based on the impact measured over a typical mission i.e. standard flight profile optimized for minimum fuel, evaluated the influence of essential design parameters (such as range, cruise altitude, mach and wing span) on the climate impact and estimated the improvements in mitigation potential with alternate fuel and technologies. Additionally, analyzing the emission distribution along the route network for the design process has also become a subject of interest as non-CO_2 emissions have spatial variability in their effects. However, the adaption of a single aspect into the optimization process is likely to provoke penalties in other aspects due to interdisciplinary characteristics of the air transport. Hence, a multidisciplinary optimization approach is required to consider the interdependencies between aircraft design, new technologies, operations, emissions, atmospheric effects and economics. Within CATS project [3] such an approach to redesign a reference aircraft was employed by studying the mitigation potential over a specific aircraft's global route network from varying the initial cruise altitude and cruise mach number. The aircraft design was then optimized for minimizing fuel consumption for a combination of initial cruise altitude and mach number for which a mitigation potential was evaluated. The calculated new design demonstrated increased mitigation potential for relatively lower monetary cost increase, compared to a climate optimized route network. Despite the identified potential to mitigate aviation climate impact through climate-change-driven aircraft design, developing a closed loop design optimization framework with an environment impact parameter still remains a challenge as no climate model has demonstrated sufficient characteristics to evaluate the variations in climate impact from design changes and does not require high computation efforts. GLOWOPT is set to directly contribute to this challenge by developing innovative CFAD that allow for a minimization of the climate impact of next-generation aircraft within the conceptual design phase. The design changes within this project will consider the main design variables, promising technologies and propulsion concepts speeding up the development of green aircraft.

The conceptual design of aircraft can be performed by relying on multidisciplinary design optimization. This process can be automated and embedded in a software environment. The Aircraft Design Initiator, an automated design framework, is specifically developed to assess the effect of top-level requirements, new aircraft configurations, and new aviation technologies on aircraft performance metrics [14]. Such a framework can be used to quickly investigate the effect of changing TLARs or the effects of technology infusion. In GLOWOPT, this tool will be utilized for producing feasible conceptual aircraft designs that minimize the climate functions.

For the MDO process, an envelope of operational and engine/airframe parameters needs to be established as these will define the design space for the climate optimized aircraft design. The operational parameters are determined based on the fleet analysis discussed in the previous section. The range of engine and airframe parameters, which have an impact on aircraft performance such as bypass ratio, overall pressure ratio, turbine inlet temperature, type of high lift installed, fuselage slenderness ratio etc., are established from the state-of-the-art technologies. Additionally, a technology compatibility matrix is established and compliance with operational constraints from ATM (i.e. SESAR) is ensured.

Using the CFAD, a series of optimized aircraft can be synthesized that fulfils CS-25 requirements, top-level aircraft requirements, and operational constraints while minimizing the climate function. Considering the large design space, in terms of possible technology combinations, operational parameters, airframe parameters and engine parameters, a search strategy will be employed for finding an optimum. The attributes of these climate optimized aircraft in terms of geometry, characteristic weights, thrust-to-weight ratio, wing loading, etc., can subsequently be used for a more in-depth analysis of each design and its impact on other disciplines such as noise or cash operating cost as well as for a more in-depth climate impact analysis.

3. ASSESSMENT AND VALIDATION

In order to evaluate the usability of the CFADs and validate the GLOWOPT approach a detailed assessment is conducted using a higher-fidelity simulation.

Reference aircraft will be selected for each market segment which will serve as a baseline for comparing the climate optimized aircraft design. Emission inventories based on the emission distributions along each route within the route network will be generated for reference aircraft and climate optimized aircraft designs. GRIDLAB, a tool developed for environmental analysis of new technologies and operational concepts for aviation [15], will be used to calculate the input inventory for the climate impact assessment based on the characteristic route network and fleet as well as on the flight performance of the aircraft designs. The resulting climate impact, both for reference and climate-optimized aircraft is estimated using a climate model, e.g. AirTraf [11] or AirClim [12]. That way the actual use of the aircraft within the network and the corresponding climate impact is analysed more accurately, which allows for an assessment and iterative adaptation of the CFADs. Moreover, a comparative study for the operating cost vs climate mitigation assessment of the synthesised designs will be carried out from estimating the direct operating costs resulting from the operations of the reference and the climate-optimized aircraft on the selected market segment's route networks.

4. SUMMARY AND CONCLUSION

This paper presents the GLOWOPT approach to develop and validate novel CFAD. Those functions constitute an easy-to-use tool, which can be integrated into existing aircraft synthesis workflows without high adaptation effort. It will be made available to the relevant stakeholders including aircraft manufacturers, and thus allows for the development of new aircraft with a significantly reduced impact on global warming. The GLOWOPT approach accelerates the development of 'green' aircraft and therefore contributes to the high-level objectives of the Clean Sky 2 programme as well as the ACARE goals and helps to fulfil the Paris Agreement. It is important to note, that the CFAD will not only consider CO_2 and NO_x effects but also include other relevant effects of non-CO_2 emissions on the climate such as H_2O and contrails.

5. ACKNOWLEDGEMENTS

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