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ATM4E: A concept for environmentally-optimized aircraft trajectories

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ABSTRACT:

Trajectory optimisation is one option to reduce air traffic impact on environment. A multi-dimensional environmental assessment framework is needed to optimize impact on climate, local air quality and noise simultaneously. An interface between flight planning and environmental impact information can be established with environmental cost functions. In a feasibility study such multi-dimensional assessment can be applied to the European Airspace. The project ATM4E within the frame of SESAR2020 has spelled out the objective to develop such a concept and to study changing traffic flows due to environmental optimisation.

1. Introduction

Beyond the desire to minimize fuel use and hence CO_2 emissions, currently the consideration of environmental aspects in en-route flight planning has not been operational practice. The reason for this is a low TRL (technology readiness level) of a flight planning method that considers a multi-dimensional environmental impact assessment and a lack of scientific support to motivate environmental flight planning. In common practice, route optimization is driven by cost minimization, hence those environmental aspects which translate into direct operating costs (DOC), are taken into account. E.g. emissions of carbon dioxide enter into route optimization as they directly correlate to fuel consumption. Other environmental impacts indirectly enter in DOC optimization, e.g. noise or nitrogen oxide (NO_x) emissions near an airport in case of associated airport charges. However, air traffic emissions contribute to anthropogenic warming by around 5% by a CO_2 and non-CO_2 impacts (Sausen und Schumann, 2000, Lee et al., 2010).

Previous research activities have shown that changing aircraft trajectories to avoid climate sensitive regions has the potential to reduce the climate impact of aviation (Green et al., 2005). Specific studies have been published (e.g. Klima, 2005, Sridhar et al. 2011, Schumann et al., 2011) and presented trade-offs between climate-optimised and cost-optimised trajectories for different regions of the earth (cross-polar, North Atlantic, Pacific traffic). Although several optimization tools exist that incorporate more detailed aircraft performance data and that perform a full 4D optimization, none of these are able to process climate-cost functions to calculate climate-optimized trajectories. The European project REACT4C (Matthes et al., 2011) went a step beyond and focused on climate-optimized routing strategies primarily in the North Atlantic airspace using climate-cost functions (Grewe et al., 2014a). ATM constraints and operational boundary conditions were assumed leading to optimal routes and vertical flight profiles that follow the existing ATS route system and include step climbs where appropriate. Based on a detailed weather classification (Irvine et al., 2013) five representative days for winter and three days for summer were selected to calculate Climate-Cost-functions for these individual days. These comprise the impact of a local emission on climate and are used in a traffic simulator to optimize the traffic flow with respect to climate impact. The results from REACT4C (Grewe et al., 2014b) indicate, in a case study, a large mitigation potential with a reduction of the climate impact of around 25% at a cost increase of about 0.5% for westbound trans-Atlantic flight and less for eastbound flights (Figure 1).

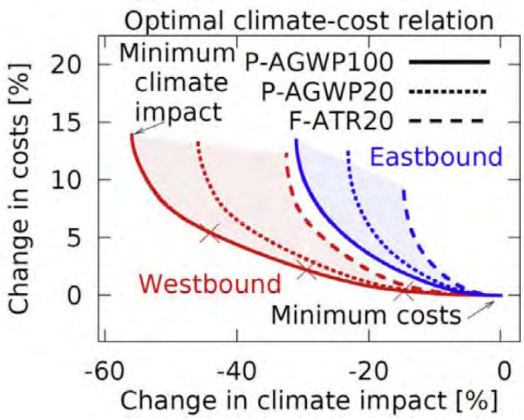

Figure 1: Relation between climate impact reduction and cost increase for re-routing of trans-Atlantic air traffic for a single day in winter (Grewe et al., 2014b).

However, systematic and simultaneous consideration and optimization of environmental impacts, comprising climate impact, air quality and noise issues, are currently lacking. The exploratory research project ATM4E (Air Traffic Management for Environment, SESAR2020) addresses this gap and explores the feasibility of a concept for a multi-dimensional environmental assessment of ATM operations working towards environmental optimization of air traffic operations in the European airspace.

The study presents This concept aims integrating existing methodologies for assessment of the environmental impact of aviation, in particular a concept for climate-optimization which has been developed in a feasibility study of the North Atlantic in the EU funded aeronautics project REACT4C (FP7).

Therefore, the objective of this paper is to present a concept for a multi-dimensional environmental cost function (ECF) framework for trajectory planning, which includes local and regional air quality impacts (for key pollutants) and noise together with climate impact assessment (Section 1). This concept aims integrating existing methodologies for assessment of the environmental impact of aviation, in particular a concept for climate-optimization which has been developed in a feasibility study of the North Atlantic in the EU funded aeronautics project REACT4C (FP7). Second, we show how the required interface between ATM and environmental impact can be established by introducing environmental change functions (Section 2). In Section 3, we describe overall approach to apply such environmental optimization framework to the European ATM Network in this exploratory research project (SESAR2020), and conclude our study with innovative potential, providing a perspective on the longer term implementation and benefits.

2. Concept for multi-dimensional environmental trajectory optimization

The concept aims at evaluating the multi-dimensional impact of aircraft flight routes on the environment (climate, air-quality, noise) through an extensive modelling approach that incorporates a large number of processes. The feasibility of such a concept for an environmental assessment of ATM operations is explored working towards environmental optimisation of air traffic operations in the European airspace.

Existing methodologies for assessment of the environmental impact of aviation are integrated, in order to evaluate the implications of environmentally-optimized flight operations to the European ATM network, considering climate, air quality and noise impacts.

2.3. Climate optimisation of trajectories

A modelling concept for climate-optimisation which has been developed in a feasibility study for the North Atlantic is expanded to a multi-dimensional environmental impact assessment, covering climate, air quality and noise.

2.2. Environmental change functions

ATM4E links to REACT4C and takes advantage of the large amount of data available from that project. The CCFs and meteorological data from REACT4C are analysed to deduce relations (algorithm) between meteorological information and the CCF, which then depict the algorithm based CCFs as part of the algorithm based ECF, which include additional environmental impact (local air quality, noise). This algorithm based ECF are used to simulate air traffic flows for any day, and are no longer restricted to the initial selected days in REACT4C.

2.3. Trajectory optimization

This is done by using a trajectory optimization module (TOM) which will be adapted to process environmental cost functions as optimization criteria for the trajectory planning (Niklass et al., 2015). In parallel the Earth-System-Model (Jöckel et al., 2016) which includes the traffic simulator AirTraf as a submodel (Yamashita et al., 2015), constitutes a platform to verify the climate impact reduction for a multitude of weather situations and the effectiveness of the algorithm based ECF. A final hot-spot analysis using a network management model (NFE) for the EATMN will be conducted to highlight areas with a significant increase of air traffic density due to the changed flight planning concept (Lau et al., 2015).

Different traffic scenarios (present-day and future) are analysed to understand the extent to which environmentally-optimized flights that are planned and optimized based on multi-dimensional environmental criteria (assessment) would lead to changes in air traffic flows and create challenges for ATM. These findings are used to prepare a roadmap compliant with SESAR2020 principles and objectives which would consider the necessary steps and actions that would need to be taken to introduce environmentally-optimized flight operations on a large scale in Europe.

Built on the successful REACT4C, the methodology followed is based on the synergistic use of a state of the art climate-chemistry model coupled with the appropriate sub-models (for calculating the radiative forcing from emissions and contrails), a traffic simulator and local-air quality and noise models in order to quantify the environmental impact of aviation.

As depicted in Figure 2 ATM4E scope can be attributed to the Trajectory Management Framework responsible for the planning of optimized 2D/3D routes and the processing of Business and Mission trajectories within the SESAR Operational Concept. The project addresses civil aviation only (Business trajectory) and focuses on commercial air transport based on scheduled flight movements.

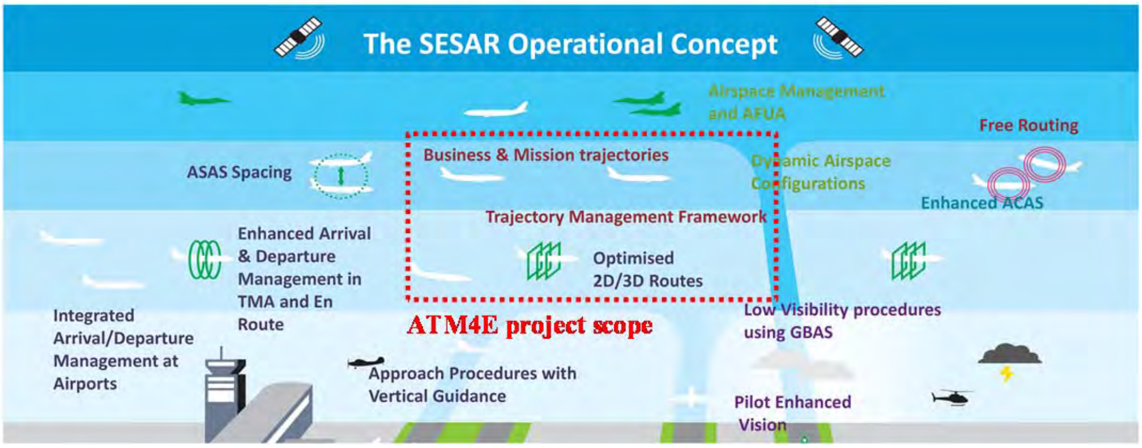

Figure 2: The SESAR Operational Concept with the contribution from ATM4E indicated in red.

2.4. Overall approach

The overall approach is a modelling study which relies on comprehensive model calculations in order to construct and assess ECFs, hand them over to a trajectory planning tool and evaluate the impact on network flows. For typical meteorological cases detailed calculations of environmental impact will be performed, in order to quantify environmental impact and options to mitigate it.

Combining state-of-the-art CCFs derived from comprehensive climate-chemistry-simulations with detailed meteorological data, the project establishes an interrelation, which allows the development of a method for a fast estimation of CCFs based on a number of meteorological parameters, e.g. temperature, humidity, wind speeds and directions. These “algorithm based ECF” provide climate impact information on a day-to-day basis and can be used in the day-to-day flight planning process to identify climate-optimal routes. Integrating additional components into the ECF (local air quality, noise) in the analysis produces a multi-dimensional environmental assessment, allowing the evaluation of interactions and trade-offs. The inclusion of the new elements in the ECF takes into account the need for flexibility and the ability to incorporate new understanding, as it becomes available, as key requirements.

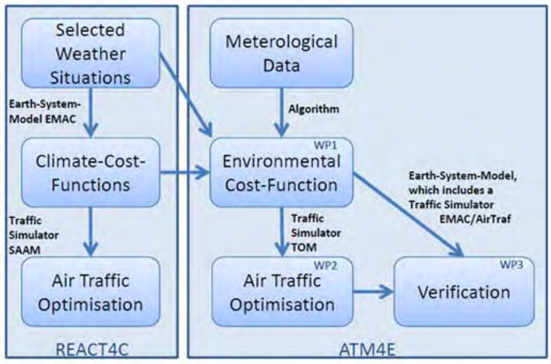

Figure 3: Schematic workflow of REACT4C and the link to the workflow of ATM4E.

3. Environmental change functions (ECF) for aviation

An interface between a flight planning tool and environmental change information is established by using environmental change functions. For this purpose, distinct functions are developed for a set of environmental impacts related to aviation emissions:

- Climate impact by directly or indirectly influencing concentration of radiative active species, e.g. CO_2, ozone via NO_x emission, particles.
- Impact on local and regional air quality by influence on concentration of pollutants, e.g. particulate matter.
- Impact on noise in airport vicinity.

3.1 Climate cost function approach developed within REACT4C

Within the European research project REACT4C a concept was developed which provides a quantitative measure of sensitivity of the atmosphere to aviation emissions with regards to climate impact. Specifically, for a specific location and time of emission, the associated climate impact, e.g. in terms of temperature change over the next 20 years, per emitted unit was provided. These functions were called climate cost functions, and possessing units of e.g. 10^{-13}K/kg(NO_2). An example of such climate change function for one specific day in the North Atlantic Flight corridor is shown in Fig. 4, indicating climate impact of nitrogen oxide emissions, which is a combination of chemical ozone formation (warming) and induced change of lifetime of methane (cooling). The meteorology (geopotential height) is overlaid and wind speed indicates the location of the jet stream.

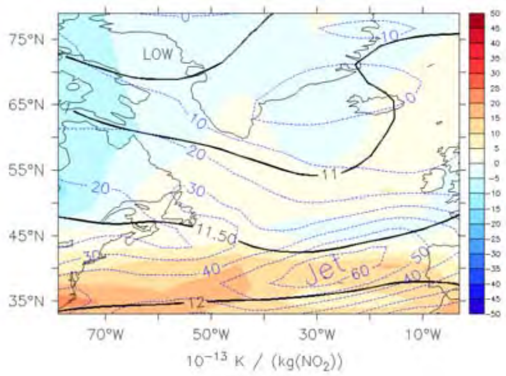

Figure 4: Climate cost functions for the metric F-ATR20 at 200 hPa and 12 UTC i.e. 20 year mean near-surface temperature change induced by an aircraft flying: combined effect of total NO_x, respectively in [10^{-13}K/kg(NO2)]. Geopotential isolines (black) and wind speed (blue) (adapted from Grewe et al., 2014b).

For any given trajectory the associated climate impact can be calculated with these CCFs, by multiplying the emission generated, as calculated by an engine model with the corresponding CCFs of the specific location of the aircraft for a specific time. Repeating this calculation all along the waypoint where an aircraft flies while summing up individual impacts allows calculating the climate impact of the full trajectories.

3.2 ECF for local air quality impact

In order to include local air quality aspects, the concept of climate change functions is expanded, leading to environmental change functions which include local air quality impacts, and in similarly noise issues. This requires integrating impacts via environmental metrics which are able to consider local impacts versus global environmental impacts.

For this purpose data on air quality impact is extracted from air quality model simulations for, e.g. NOx, PM. This data is used in order to prepare environmental change functions, which establish a link between aircraft emission and associated impact on air quality.

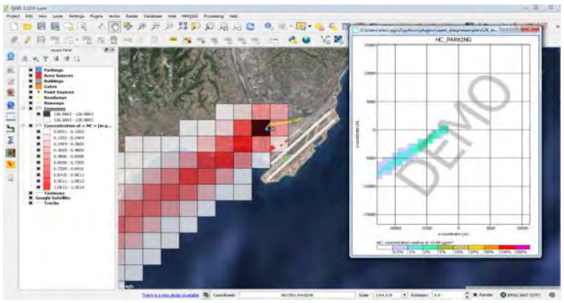

Figure 5: Air quality assessment, Open-ALAQS showing local impacts.

For a selected region and weather situation such required data is generated (Fig. 5) and delivered to a flight planning tool.

3.3 ECF on noise

In a similar process, environmental change function is generated on noise issues. For this purpose data on perceived noise impact is extracted and processed from available model simulations. In our study we use output from STAPES (Figure 6), in order to generate noise ECFs required for environmental optimization.

Figure 6: Noise contours associated to different trajectories, STAPES.

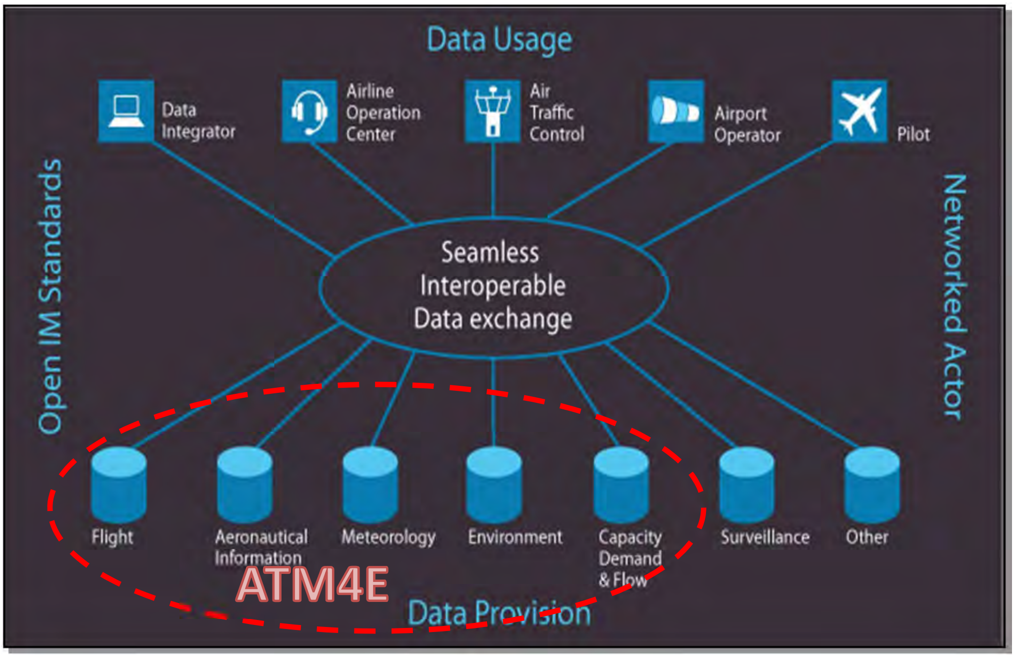

Figure 7: ATM4E in the SWIM environment.

4. Environmental optimisation of air traffic over Europe

The multi-dimensional environmental optimisation is applied for an optimisation of the European ATM network. For the analysis, samples of air traffic characteristic for selected regions in Europe are chosen. For these traffic scenarios the ECF for the relevant regions are determined based on the day-to-day meteorology. These serve as a basis for the optimization of the flight trajectories. Here, different trajectory optimization strategies are investigated. Possible strategies include optimizations for isolated environmental contributions (e.g. contrails only) as well as multi-criteria optimizations allowing for conducting trade-offs between the different effects including changes to the flight efficiency.

The approach of using ECF in the trajectory optimization is verified in two ways:

1) The reduction of the climate impact from aviation by avoiding climate sensitive regions, (e.g. regions conducive to contrail formation) by using ECFs is verified for case studies by directly simulating the atmospheric changes in an ESM coupled with an air traffic submodel.

2) The applicability of algorithm based ECF, which are developed in WP1 are verified in case studies by using both ECFs and algorithm based ECF using on the same simulation framework (EMAC/AirTraf).

Then, the resulting optimized trajectories are analysed with respect to their impact on airspace demand. For this, a Network Management modelling tool (Network Flow Environment, NFE) is used to generate a simulated network scenario including scheduled departure times. Capacity overload areas are identified and highlighted. The implications to the network are analysed and discussed in view of the achieved climate benefit and potential flight efficiency losses.

Hence, we propose to develop a method that allows a numerical efficient calculation of ECF via an algorithm based on meteorological information that could be provided in a SESAR operational framework through the System Wide Information Management (SWIM) function (Fig. 7). This algorithm based ECF can serve to expand planning tools in order to be able to quantify the environmental impact of individual aircraft trajectories (operations).

5. Innovation Potential

ATM4E aims at evaluating the multi-dimensional impact of aircraft flight routes on the environment (climate, air-quality, noise) through an extensive modelling approach that incorporates a large number of processes. Built on the successful REACT4C, the methodology followed is based on the synergistic use of a state of the art climate-chemistry model coupled with the appropriate sub-models (for calculating the radiative forcing from emissions and contrails), a traffic simulator and local-air quality and noise models in order to quantify the environmental impact of aviation.

The multi-dimensional approach followed in ATM4E pushes the boundaries of current environmental studies focused on aviation since it examines a large number of key parameters simultaneously using a pioneering approach that examines flights both en-route and at landing / take-offs. From that perspective, this study is unparalleled and has the potential to advance our knowledge of the solutions that could be put in place to limit the overall environmental impact of aviation.

The scope of this extensive effort is to enable the environmental assessment of aircraft 4D trajectories, developing free routing further with the intention to mitigate aviation environmental impact, address the issues of durable development and derive environmental impact information based on meteorological standard parameters, e.g. temperature, humidity, wind speed and direction, atmosphere stability, mixing height, visibility.

The application of an Earth-System-Model with an integrated air traffic submodel (Yamashita et al., 2015) will enable for the first time the verification of environmentally optimised re-routing strategies in a consistent simulation environment. This exploratory research will for the first time test the feasibility of flight routing accounting for climate, air quality and noise. The short-term benefits of these routings can be qualitatively assessed especially for air quality and noise since these effects directly impact European citizens. The sustainability of the air transport industry, especially with respect to the achievement of ACARE goals can be explored.

To our knowledge, this is the first time that an effort is made to simultaneously take into account climate, as well as noise and LAQ issues for the development of environmentally optimized 4D trajectories and ATM needs.

Particular focus was given on how to establish an interface between ATM and environment with such environmental change functions. For the conceptual study within ATM4E (SESAR 2020, EU) presented here these ECFs are derived from dedicated model output of atmospheric global circulation models, local air quality tools, and noise models. The overall objective on the longer term is to develop an operational multi-dimensional environmental criteria assessment in air traffic management, which considers simultaneously operating costs, network structure and environmental impacts: climate, air quality and noise.

Having such an expanded flight trajectory management available will allow in the future to assess overall environmental impact of individual trajectories, as well as to identify an environmentally optimized routing option.

6. Acknowledgement

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7. Abbreviations

ATM	Air Traffic Management
ATR	Average Temperature Response
ATS	Air Transport System
CCF	Climate change (cost) function
DOC	Direct operating cost
ECF	Environmental Change Function
EATMN	European ATM Network
EMAC	ECHAM5/MESSy Atmospheric Chemistry
LAQ	Local Air Quality
NFE	network management model
PM	Particulate matter
UTC	Coordinated universal time
NOx	nitrogen oxides
REACT4C	FP7 Project, Aeronautics

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