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FlyATM4E

FLYING AIR TRAFFIC MANAGEMENT FOR THE BENEFIT OF ENVIRONMENT AND CLIMATE

The Final Project Results Report is part of a project that has received funding from the SESAR3 Joint Undertaking under grant agreement No 891317 under European Union's Horizon 2020 research and innovation programme.

Abstract

The objective of the Final Project Results Report is to cover all the research activities performed within the research project FlyATM4E. This Report summarizes key findings from the project as well as its key achievements towards the European ATM Master Plan. Furthermore, the project reports on the achieved maturity steps, supported by a self-maturity assessment.

The overall objective of the project FlyATM4E was to develop a concept to identify climate-optimised aircraft trajectories in which Air Traffic Management (ATM) could help to provide a robust and eco-efficient reduction in aviation's climate impact and estimate mitigation potential taking into account CO_2 and non-CO_2 emissions. A systematic analysis of the spatially and temporally resolved climate impact of aviation's emissions was performed by using algorithmic climate change functions for a set of non-CO_2 impacts with a particular focus on identifying sources of uncertainties. Flight trajectory optimization and planning tools were used to explore possibilities in including uncertainties when performing climate-optimized trajectories. The project results highlight that the mitigation potential of flight trajectory optimization shows a large spatial and temporal variability due to the variability of the underlying atmospheric conditions.

FlyATM4E developed two candidate solutions targeting on identifying climate optimized trajectories. Such alternative aircraft trajectories have a lower climate effect by avoiding those regions of the atmosphere where aviation emissions have a large climate effect, e.g. by forming warming contrails or ozone formation. Candidate solution Sol-FlyATM4E-01 is an enabler solution which used temperature, relative humidity, outgoing longwave radiation and geopotential in order to calculate climate effects of aviation emissions at a given location and time. Candidate solution Sol-FlyATM4E-02 describes the necessary extension of aircraft trajectory planning processes to implement a well-informed and robust multi-objective flight planning with the goal to consider the total climate impact (CO_2 and non-CO_2 effects). The algorithmic climate change functions as defined per Sol-FlyATM4E-01 serves as an enabler for this solution in order to provide situational awareness on climate effects of aviation emissions.

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1 Executive Summary

1.1 FlyATM4E project summary

Analysis shows that controlling both CO_2 emissions and non-CO_2 effects has the potential to double the benefits available from reducing carbon emissions alone. Non-CO_2 effects such as contrail cirrus clouds (ice crystals that form behind aircraft) and nitrogen oxide (NO_x)-induced changes of ozone and methane upset the radiative balance of the atmosphere. They are strongly dependent on the weather and vary considerably according to atmospheric conditions such as air temperature, atmospheric humidity and concentrations of reactive species.

Climate-optimised trajectories aim to avoid those regions of the atmosphere where effects induced by aviation emission are large. To this end, FlyATM4E explored those weather situations and aircraft trajectories that have the potential to lead to a robust climate impact reduction despite uncertainties in atmospheric science, which can be characterised by ensemble probabilistic forecasts. Planning of these climate-optimised aircraft trajectories requires air traffic management to use spatially and temporally resolved information on the magnitude of the climate effects associated to aviation emissions during the trajectory planning process. The FlyATM4E solution relies on prototypic algorithmic climate change functions (aCCFs) to derive such climate impact information for flight planning directly from operational meteorological weather forecast data. By combining the individual aCCFs of water vapour, NO_x and contrail-cirrus, i.e. merged non-CO_2 effects, it becomes possible to generate aCCFs that describe the overall climate impact of non-CO_2 aviation emissions and identify weather situations with high mitigation potential, including an uncertainty assessment. The overall modelling study explores climate-optimisation of aircraft trajectories and estimates benefits. The analysis of sample flights showed different changes in average temperature response with respect to cost or climate optimum and trade-off trajectories within the set of pareto-optimal solutions.

The FlyATM4E solutions enable ATM to identify climate-optimised aircraft trajectories which provide a robust and economically efficient reduction in aviation's climate impact. These results suggest that applying these candidate solutions have the potential to reduce the aviation's climate footprint by low or no additional costs.

1.2 Technical Summary

The objectives of the project FlyATM4E were to develop a concept to identify climate-optimized aircraft trajectories in which operational measures can help to provide a robust and eco-efficient reduction in aviation's climate impact and estimate the mitigation potential considering CO_2 and non-CO_2 emissions. This includes the advancement of concepts that enable to assess the climate impact of aircraft operations which integrate an adequate representation of uncertainties, including CO_2 and non-CO_2 effects from weather forecast as well as climate science. Further, aviation's climate impact mitigation potential by developing robust flight planning algorithms have been investigated. Based on these outcomes, eco-efficient aircraft trajectories and related weather situations, which enable a reduction of both climate impact and operational costs ("win-win") by avoiding ATM inefficiencies have been identified. Results of the project have been used to provide recommendations for target stakeholders on policy actions and supporting measures to implement eco-efficient aircraft trajectories.

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FlyATM4E delivered a systematic analysis of the spatially and temporally resolved information on the climate effect of aviation's emissions. This analysis for different seasons, geographic regions and flight altitudes was performed by using algorithmic climate change functions for a set of non-CO_2 impacts including a particular focus on identifying sources of uncertainties. Flight trajectory optimization and planning tools were used to explore various possibilities on how to include uncertainties when identifying climate-optimized trajectories. For a systematic case study involving a set of typical winter days and summer days (June and Dec 2018), an air traffic sample was thoroughly selected for the European airspace analysing city pairs and representative traffic in 2018. The tools for trajectory optimization were applied in order to identify climate optimized trajectories: ROOST, TOM and EMAC/AirTraf. The air traffic simulator (AirTraf) was developed further to include new algorithms, which allow the selection of eco-efficient flights concerning the predefined optimization objectives, constraints and the specific weather impacts. A long-term simulation was performed with the global chemistry climate model EMAC in order to investigate the potential of finding eco-efficient flights. During the project period, large interest has been experienced from outside the project in this topic leading to participation in a series of dissemination events comprising scientific conferences, stakeholder seminars, and contacts to regulators, as well as resulting in the preparation of scientific papers.

As main conclusion, the project results highlight that the mitigation potential of flight trajectory optimization shows a large temporal variability, due to the variability of the underlying atmospheric conditions. Moreover, information on the mitigation potential of the whole air traffic sample could be used in the future as input for our optimization tools, to limit cost penalties.

In this project, two SESAR candidate solutions were proposed. An enabler solution (SOL-FlyATM4E-01) with a set of prototype algorithmic climate change functions was employed with an operational solution of climate-optimized trajectories (SOL-FlyATM4E-02) to estimate the climate impact of non-CO_2 effects. As recommendations, these formula should be expanded for future applications, as their current version has been developed considering a limited geographic (North Atlantic Flight Corridor) and temporal (summer and winter) coverage. Moreover, the use of radiative transfer models, empirical models of contrail life cycle, and climate models is recommended to compare the quantification of aviation climate impact obtained from different approaches.

2 Project Overview

2.1 Operational/Technical Context

At present, flight routes are planned on the basis of minimizing operating costs (typically based on fuel, time, and overfly charges) while complying with ATM and operational constraints. At the same time, the connectivity of the fleet network needs to be maintained in order to avoid expensive payments to passengers missing connections. Concerning aviation induced climate change, impact of CO_2 emissions is directly linked to fuel consumption, while non-CO_2 emission impacts (e.g. contrails and contrail cirrus, ozone formation caused by NO_x emissions and aerosols) rather depend on regional and seasonal variations of meteorological conditions. Different spatial and temporal scales of individual impacts have to be considered. Hence, the contribution of aviation non-CO_2 effects to global warming (and derived climate change) is more difficult to assess due to its inherent complexity and it depends on flight performance, weather conditions and time of emission.

Since local atmospheric conditions determine the net climate impact of non-CO_2 effects, we could reduce the environmental footprint of aviation's emissions optimizing the aircraft trajectories with respect to their climate impact [34], [35], [36], [37]. The mitigation potential of such climate-optimised aircraft trajectories has been investigated under representative weather patterns using a global Earth System Model, which allowed to simulate complex atmospheric processes perturbed by aviation emissions [39]. For example, considering one specific winter day, it was found that the climate impact of westbound trans-Atlantic flights could be reduced by 25% with a 0.5% increase in costs [39]. Therefore, these examples showcased the possibility to reduce the climate impact of aviation eco-efficiently, i.e. with low cost penalties. To generalize these findings under any weather conditions, algorithmic Climate Change Functions (aCCFs) were developed [40][24] (a detailed description of the aCCFs is given in Deliverable D2.1 [3]). As a result, these aCCFs could be employed in tools that optimize flight trajectories under a large number of atmospheric situations. This is as the natural variability of atmospheric conditions has to be taken in account while evaluating the mitigation potential of climate-optimised trajectories.

FlyATM4E identified these weather situations and aircraft trajectories, which lead to a robust climate impact reduction despite uncertainties in atmospheric science that could be characterised by ensemble probabilistic forecasts. The project formulated recommendations on how to implement these strategies in meteorological (MET) products and enabled ATM not only to understand these possibilities to reduce aviation's climate impact, but also how to implement such eco-efficient routing.

2.2 Project Scope and Objectives

Table 1 summarizes the project scope as outlined in the Grant Agreement.

Table 1: Scope of FlyATM4E as written in the Grant Agreement. ATM = Air Traffic Management, MET = meteorological.

Scope	FlyATM4E's Response
Proposals may investigate innovative operational changes to ATM aiming at reducing the environmental impact from aviation. These actions should consider different aspects of environmental impact, e.g. their effect in the context of global and/or long-term phenomena such as climate change, global warming and changes in the frequency and severity of extreme weather or ash-cloud formation on ATM operations.	**Investigate** the use of robust algorithmic Climate Change Functions (R-aCCFs) for the planning of robust eco-efficient trajectories as an innovative operational change to ATM and airspace users, which aims at reducing the environmental impact of CO_2 and non-CO_2 effects. **Evaluate** different aspects of environmental impacts also by linking to other research initiatives, learning from best practice on provision of MET data products within the current ATM system.
Proposals may also research to secure the proper integration of existing and possible new meteorological products into ATM for example to reduce the vulnerability of the ATM system to local weather phenomena and to improve the prediction of 4D Trajectories and network forward planning to enable a minimisation of consequential weather-related delays.	**Establish** a method to apply EPS weather forecast to determine atmospheric variability as a MET product in order to identify atmospheric situations enabling to fly robust eco-efficient aircraft trajectories. **Integrate** environmental impact information in trajectory planning allowing early planning of trajectories and usage of air space, avoiding those regions with high climate sensitivity to emissions.
Research activities may focus on the development of a concept for using very high-resolution, very short-range forecasts using numerical weather prediction models and observational data assimilation, and assess the need of new MET data/products.	**Identify** the need for novel MET data and products, which would enable implementing eco-efficient trajectories, by liaising with other actions targeting on developing concepts for using NWP models and observational data assimilation. This allows optimisation in enhanced ATM system under combined criteria, e.g. time- and eco-efficiency as two constraints.
The incorporation of ensemble weather information into decision-support tools, adapted for different ATM stakeholders may also to be investigated.	**Integrate** ensemble prediction system (EPS) weather forecast in an expanded ATM system in order to explore robust conditions.
This topic is linked to ACARE Challenge 3.	**Use** established collaboration with thematic ACARE working groups (WG3, WG5) to assure efficient transfer of improved knowledge and understanding.

The **overall objective** of the project FlyATM4E was to develop a concept to identify climate-optimised aircraft trajectories in which Air Traffic Management (ATM) could help to provide a robust and eco-efficient reduction in aviation's climate impact and estimate mitigation potential, taking into account

CO_2 and non-CO_2 emissions through MET data, ensemble prediction and eco-efficient trajectories. FlyATM4E considered the effect of emissions of CO_2, NO_x, H_2O, and particulates on the atmosphere via concentration changes of radiative active species, comprising effects on ozone, methane, and contrail-cirrus.

This overall objective was subdivided into four **specific objectives**, which are to

Objective O1: *advance concepts to assess the **climate impact of ATM operations** which integrates an adequate representation of uncertainties*, including CO_2, contrails, ozone, methane and water vapour climate effects, from weather forecast as well as climate science, and to provide concepts for climate information enabling eco-efficient aircraft trajectories.

FlyATM4E research towards O1: A systematic analysis of the spatially and temporally resolved climate impact of aviation emissions was performed by using the available algorithmic climate change functions for a set of non-CO_2 impacts (WP1). Particular focus was given on identifying sources of uncertainties in the dataset, and a comprehensive description has been developed for inclusion in the technical note on the availability of aCCFs (D1.1 [1]). D1.2 [3] reports an improved version of the aCCFs by including a set of educated guess factors.

By the generation and publication of the open source Python Library CLIMaCCF [23], O1 was successfully achieved.

Objective O2: *investigate aviation's climate impact **mitigation potential** by developing **robust flight planning algorithms*** through the integration of uncertainties from the climate impact analysis and ensemble weather forecasts in ATM.

FlyATM4E research towards O2: The applied flight trajectory optimization and planning tools (Trajectory Optimisation Module (TOM) and Robust optimisation of structured airspace (ROOST)) were used to explore possibilities in including uncertainties when performing climate-optimized trajectories. A set of traffic samples was thoroughly selected considering appropriate boundary conditions, i.e. the time-frame and the required meteorological data. Various sources of uncertainties, e.g. modelling approach in calculating the climate impact of different effects, were analysed. Detailed results can be found in D2.1 [4] and D2.2 [6].

Two experiments, namely Experiment #2 and Experiment #3 as defined in the Experimental Plan (see Appendix B.6.5), were conducted to validate O2, which was successfully achieved.

Objective O3: *identify **eco-efficient aircraft trajectories** and related **weather situations,*** which enable a reduction of both climate impact and operational costs **('Win-Win')** by avoiding ATM inefficiencies; or which largely reduce the climate impact of aviation at almost unchanged costs by avoiding extreme climate sensitive regions.

FlyATM4E research towards O3: The air traffic simulator (AirTraf) was developed further to include new algorithms, which allowed the selection of eco-efficient flights concerning the predefined optimization objectives, constrains, and the specific weather impacts. A long-term simulation was performed to investigate the potential of finding eco-efficient flights. Results on eco-efficient flights and "win-win" situations are reported in D3.1 [7] and D3.2 [9].

Two experiments, namely Experiment #1 and Experiment #4 as defined in the Experimental Plan (see Appendix B.6.5), were conducted to validate O3, which was successfully achieved.

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Objective O4: ***provide recommendations*** *for target stakeholders* on policy actions and supporting measures *to implement eco-efficient aircraft trajectories* enabled by a better understanding of the climate impact of individual aircraft trajectories.

FlyATM4E research towards O4: The External Experts Advisory Board has been established bringing together key stakeholders on aviation and climate impacts, with regular virtual meetings taking place. During the project period, large interest has been experienced in this topic leading to participation in a series of dissemination events comprising scientific conferences, stakeholder seminars, and contacts to regulators, as well as resulting in the preparation of scientific papers in order to assure scientific progress (see D4.2-D4.4 [11], [12], [13] for details).

Concluding these exchange activities, a series of recommendations have been provided in D4.3 [12], thus, fulfilling O4.

2.3 Work Performed

In this section, the scientific work performed is described. Models and methods that were used, further developed and adapted in the project, are presented. Moreover, the simulation and validation exercises show their application. More technical details can be found in the related deliverables.

The leading concept for the development of a robust flight planning mechanism to identify eco-efficient trajectories are the so-called algorithmic Climate Change Functions. Within the preceding project ATM4E, these mathematical formulations were derived in order to compute the climate impact of certain amounts (and specific species) of aircraft engine emissions as a function of the geographical location, altitude and prevailing meteorological conditions determined by forecast data in real-time. The formulations of algorithmic functions are critical from an operational point of view since, in order to consider these eco-efficient routes in flight planning, they need to be available within a dedicated time frame.

The concept of these aCCFs has been successfully demonstrated in previous research [35][37], however these functions were applied in a deterministic way. Since weather forecasts at their core are bound to uncertainties, uncertainties of MET data needed to be represented. Within FlyATM4E, these uncertainties are integrated by means of ensemble prediction system (EPS) forecasts. The EPS produces a collection of forecasts for a specific prediction time and constitutes a representative sample of the potential future states of the atmosphere taking into account minor variations in the initial conditions considered for the forecasts. Additional uncertainties are introduced into the climate impact assessment due to the models applied for the assessment. It was the key objective of FlyATM4E to develop a set of robust aCCFs which was used to compute flight trajectories for a representative subset of intra-European air traffic of the year 2018 with the objective to reduce climate impact and operating costs at the same time. This could result mainly in two result-scenarios (Figure 1):

- A reduction of both climate impact and operating costs – a so-called “win-win”-situation;
- A significant reduction of climate impact with nearly unchanged operating costs – a so called eco-efficient approach.

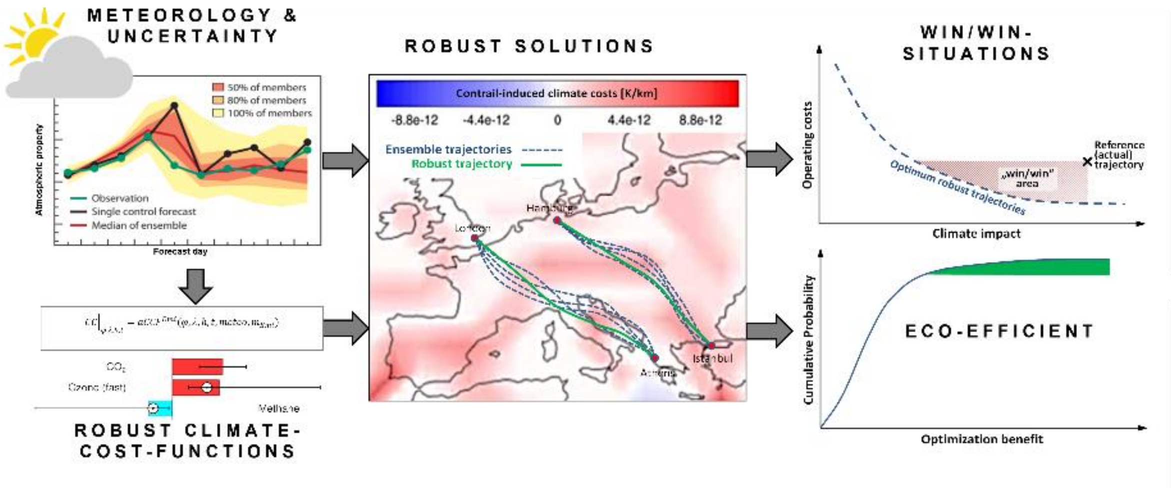

Figure 1: Schematic illustration of FlyATM4E concept

The applied methods and tools are presented in the following chapters within the context of the work package (WP) they were developed/ applied in. The overview (Figure 2) is meant to clarify the work executed in each WP as well as their interaction. A set of prototype aCCFs generated within WP1 was provided to WP2 and WP3. It describes the impact of local emissions on climate change by changes in CO_2, water vapor, ozone and methane concentrations as well as contrails. Uncertainties associated with these aCCFs and weather forecast were considered in WP2 during the optimisation of robust trajectories. Within WP3, the possibility to reduce costs and climate impact ("win-win" and eco-efficient situations) was investigated. Co-operating with WP1, the underlying weather situation was investigated in order to suggest a revision of the applied aCCFs and indicate situations with high mitigation potential.

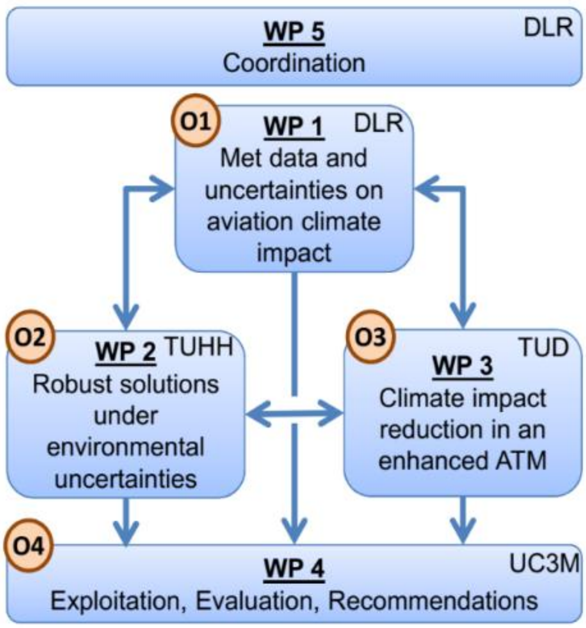

Figure 2: Interaction of the FlyATM4E work packages

2.3.1 Work Package 1 – Met data and uncertainties on aviation climate impact

Work package 1 focused on the enhancement of aCCFs by providing spatially and temporally resolved quantitative information on climate impact of individual emissions. The aCCFs cover both the global CO_2 and non-CO_2 effects of aviation, the latter accounting for ⅔ of total climate impact [41]. Uncertainties raising from atmospheric variability, predictability and low level of scientific understanding were incorporated by means of EPS weather forecasts.

The aCCFs originate in the EU project REACT4C, in which climate change functions (CCFs) were calculated in climate model simulations for NO_x and H_2O emissions, and for persistent contrail-cirrus over the North-Atlantic region for specific days of the year. Note that for these days, representative weather types in summer and winter were considered. These CCFs provide a measure of the climate impact by using the average temperature response over the future time period of 20 years (ATR20).

Determining the ATR20 by climate model simulations is computationally very demanding. Thus, rendering is operationally unsuitable for operational trajectory optimisation. To overcome this constraint, statistical methods were applied to derive algorithmic climate change functions by linking the CCFs computed in climate model simulations to specific meteorological data, e.g. temperature of geopotential height. By using MET data variables available on much shorter notice and due to their mathematical formulation, these generated aCCFs could provide climate impact estimations in a much faster way. Hence, numerical weather prediction models used for flight planning can provide the necessary data in the required time scale to operationally optimise trajectories.

Task 1.1 Provision of algorithmic climate change functions

The main goal of Task 1.1 was to enhance the aCCFs developed in the previous research Project ATM4E, provide these updated aCCFs to WP2 and WP3 as well as developing a concept for integration of robustness information. Furthermore, it was aimed to identify preferable areas in which the so-called “win-win” and eco-efficient situations may occur.

Task 1.2 Analysis of uncertainties

In Task 1.2, the focus lied on the determination of uncertainties which are linked to climate science by using EPS weather forecast. This information was then provided to WP2 for the robustness analysis of climate optimised trajectories under consideration of uncertainties.

2.3.2 Work Package 2 – Robust solutions under environmental uncertainties

Task 2.1 Scenario and methodology definition

The main goal of Task 2.1 was the definition of a suitable traffic scenario considering available traffic and MET data. Since the applied aCCFs were highly dependent on time and location of emission as well as prevailing meteorological conditions, specific days for March, June, September and December were selected to cover seasonal changes while avoiding days of high convective activity. The Experimental Plan (Appendix B) describes the steps that were performed to define a representative air traffic sample (Section B.6.1).

Task 2.2 Optimisation and analysis of sample flight trajectories

The focus of Task 2.2 was the integration of uncertainties with regard to climate impact modelling into the optimisation tools applied within WP2. Once the tools were adapted to consider uncertainties into the optimisation, optimised trajectories were calculated for the traffic scenario and days selected in task 2.1. By considering uncertainties in the optimisation, the spread of mitigation efficiency could be estimated. With this information, the robustness of eco-efficient trajectories could be assessed in terms of mitigation potential. The experiments conducted to complete this task followed the approach described in Section B.6.2 of the Experimental Plan. In the following paragraphs, we summarize the main characteristics of the tools that were employed.

2.3.2.1 Trajectory Optimisation Module (TOM)

TOM is a tool to continuously optimise aircraft trajectories based on an optimal control approach. Optimised aircraft trajectories are determined by identifying a control input which minimises a cost functional which may be defined as weighted sum of direct operating costs, fuel burn, emissions and climate impact. Additionally, dynamic constraints as well as control, state and path limitations can be included in order to specify the optimization problem. The continuous optimal control problem is then transformed into a nonlinear programming problem (NLP) and is finally solved using standard NLP solvers.

2.3.2.2 Robust optimisation of structured airspace (ROOST)

ROOST is a fast graph-based optimisation algorithm capable of determining robust aircraft trajectories in the structured airspace considering meteorological uncertainty, characterized by EPS forecast [4]. The concept obtained from robustness in this method is the determination of aircraft trajectories considering the performance of all possible realizations of meteorological variables provided within the EPS weather forecast. In other words, instead of planning a trajectory based on one forecast in a deterministic manner, the trajectory is optimised considering the overall performance obtained from ensemble forecasts. From the operational point of view, the optimised trajectory is tracked as determined and the performance in terms of variables such as fuel burn, arrival time, climate impacts is impacted by uncertainty.

2.3.3 Work Package 3 – Climate impact reduction in an enhanced ATM

Task 3.1 Optimisation of trajectories to reduce climate and cost impacts

The Trajectory Optimisation Module was adapted to allow for actual flight procedures and to process aCCFs as defined and delivered by WP1. For individual sample cases, 4D trajectories were calculated to include an eco-efficient balance between climate impact reduction (e.g., contrail formation or climate-sensitive regions are avoided) and related costs. Finally, so-called “win-win” situations were identified and the underlying meteorology was analysed for an improved characterisation of these situations. This task addressed the research hypothesis RH/5 (Section B.4) employing the approach described in Section B.6.3 of the Experimental Plan.

Task 3.2 Identification of strategies which largely reduce climate impact

In Task 3.2, the objective was to identify eco-efficient situations, i.e. conditions for which large reductions for climate impact could be achieved at low cost penalties. Therefore, this task aimed at testing the hypothesis RH/2 presented in the Experimental Plan (Section B.4). The tool selected to address this task was the air traffic simulator AirTraf, which is coupled with the ECHAM/MESSy Atmospheric Chemistry model (EMAC).

2.3.3.1 EMAC

Using an Atmospheric Chemistry model, FlyATM4E was able to optimize the air traffic sample over a large number of weather patterns and, therefore, to take into account the effect of the natural atmospheric variability on different trajectory optimization strategies. To identify eco-efficient routings, the AirTraf sub-model has been further developed. It employs now a new approach for the resolution of Multi-Objective Optimization problems, and includes Multi-Criteria Decision Making Methods for the selection of trade-off optimal trajectories. The climate impact from each flight was calculated with the ACCF sub-model, which has been adapted and verified based on the results of WP1. The new modelling chain allowed to optimize trajectories under a multitude of weather patterns, covering a whole year of simulation (from 1 December 2017 to 1 December 2018). In the next sub-section, the main developments in the ACCF and AirTraf sub-models of EMAC, which are reported in more detail in the Deliverable D3.2 [9], are summarised.

EMAC sub-models ACCF and AirTraf

Based on WP1 results, the ACCF sub-model has been updated. As a result, the user can now (1) select the climate metric and time horizon used to quantify the climate impact of the simulated flights, e.g. ATR20 to account for an increasing future emission scenario (F-ATR20); (2) take into account the efficacy of different climate impacts. Moreover, primary mode ozone (PMO) (i.e. long-term decrease in the background ozone as result of a methane decrease) effects and "educated-guess" factors have been included. The estimation of the contrail climate impact by the ACCF sub-model has been revised and compared with the literature (e.g. [42]).
The ACCF output is used by AirTraf to optimize aircraft routes with respect to their climate impact, taking into account only the cruise phase of the flight. A new version of the AirTraf sub-model has been developed, and it now efficiently solves Multi-Objectives Optimization Problems. Different solution-picking methods have been implemented in the new AirTraf model, to select a single trade-off option, among the set of Pareto-optimal solutions.

2.3.4 Work Package 4 – Exploitation, Evaluation, Recommendations

Task 4.1 Establishment and coordination of stakeholder exchange

Within Task 4.1, an advisory board (AB) was established. The AB was composed of an expert group of six stakeholder organisations (Airbus, Eurocontrol, FlightKeys, Leonardo, Lufthansa, NATS) and assured relevant feedback from other organisations as well as industry. Regular meetings with the AB in which documents and presentations were exchanged (i.e. on concepts for robust solutions, case studies for "win-win" situations or eco-efficiency) were held and revised. Besides this, SJU was kept informed on significant events of FlyATM4E and exchange of knowledge was assured with external partners (achievements, risks and mitigation, etc.). Task 4.1 was finalised with a dissemination webinar of final results.

Task 4.2 Evaluate FlyATM4E results

The main goal of Task 4.2 was the evaluation of results generated within the project. The environmental impact of ATM operations was assessed, specifically robust solutions considering atmospheric modelling uncertainties, including "win-win" or eco-efficient solutions. Besides the results themselves, the possibilities or the implementation of these solutions were discussed, including a general evaluation of showstoppers and hurdles encountered during the generation of results. By the execution of an hindcast analysis and comparison with actual solutions, the practical implementation of solutions could be assessed and more experience gained. For this, the interaction between various stakeholders from flight planning to flight realisation as well as identification of data requirements were of relevance.

Task 4.3 Disseminate project results and derive recommendations

Finally, Task 4.3 was focused towards the dissemination of project results and the derivation of recommendations based on these results. These recommendations were elaborated in strong collaboration with the advisory board and external stakeholders. The dissemination took place through various channels such as the project website, social media, scientific communication channels, a project video and open access publications. In the meantime, intermediate results were presented to the public via scientific conferences and conference proceedings and to industry and stakeholders.

2.3.5 Work Package 5 – Coordination and Management

Work package 5 performed the overall project management, including financial, legal and administrative management of FlyATM4E. Besides a detailed Project Management Plan (PMP), the organisation and roles, as well as the work breakdown structure and schedule were developed and maintained. In order to support the project consortium, a group of external experts was established and advised on the road ahead and the quality assurance on outputs generated within the project. The objectives for each task are the following:

Task 5.1. Project management and implementation

Within Task 5.1, the project management was performed compliant with SESAR Program Management and Grant Requirements. The PMP was prepared for SJU approval, including communication and exploitation plans and compliant schedules. Deliverables and technical reports were reviewed for quality assurance and coordination of deliverables with SJU took place.

Task 5.2 Regular project meetings and reports

During the course of FlyATM4E, WP5 organised regular project meetings, i.e. Kick-Off, Intermediate Review meetings and finally a project Close-out meeting. For each WP and their reports, the preparation together with the project partners was coordinated and self-maturity assessments were made and embedded in the closure report.

Task 5.3 Legal, financial and administrative management

In Task 5.3, legal, financial and administrative management was performed.

2.4 Key Project Results

Resulting from and based on the previous section 2.3, the key results and main messages of FlyATM4E are described below.

- A MET service relying on an improved set of aCCFs was developed. This consistent set of aCCFs, which provide the spatially and temporally resolved information on aviation's climate impact of water vapour, NO_x induced ozone and methane changes as well as of contrail-cirrus included educated guess factors (aCCF version 1.1, [22]) and was in line with state-of-the-art understanding of aviation's climate impact (i.e. [41]). For more details see Section 2.2 of Deliverable D1.2 [3].
- Merged non-CO_2 aCCFs combine the individual aCCFs, thus they describe the overall climate impact of aviation's non-CO_2 emissions. Merged aCCFs can be generated by considering technical specifications of e.g. aircraft/engine dependent parameters and physical climate metric. For the technical implementation, the open source Python Library CLIMaCCF (available on platform Zenodo with the software DOI: 10.5281/zenodo.6977272) [23] was developed in FlyATM4E. A more detailed description of this Library see Section 3 of Deliverable D1.2 [3].
- Individual (water vapour, NO_x, contrail) and merged non-CO_2 aCCF patterns were systematically analysed over Europe using standard meteorological input data of ERA5 reanalysis data of typical summer and winter days in the year 2018. Figure **3** illustrates how the individual and merged aCCFs look like in distinct weather situations over Europe at 250 hPa for some days in June 2018. A strong variability with different synoptical weather

situations could be seen. Moreover, aCCF patterns showed a strong clear seasonal cycle and varied with cruise altitudes (see Figure 4 and 5 in Deliverable D1.2 [3]). Comparing the individual aCCFs to the merged aCCFs (Figure **3**) revealed a dominant impact of contrail cirrus aCCFs in regions in which persistent contrails are forming.

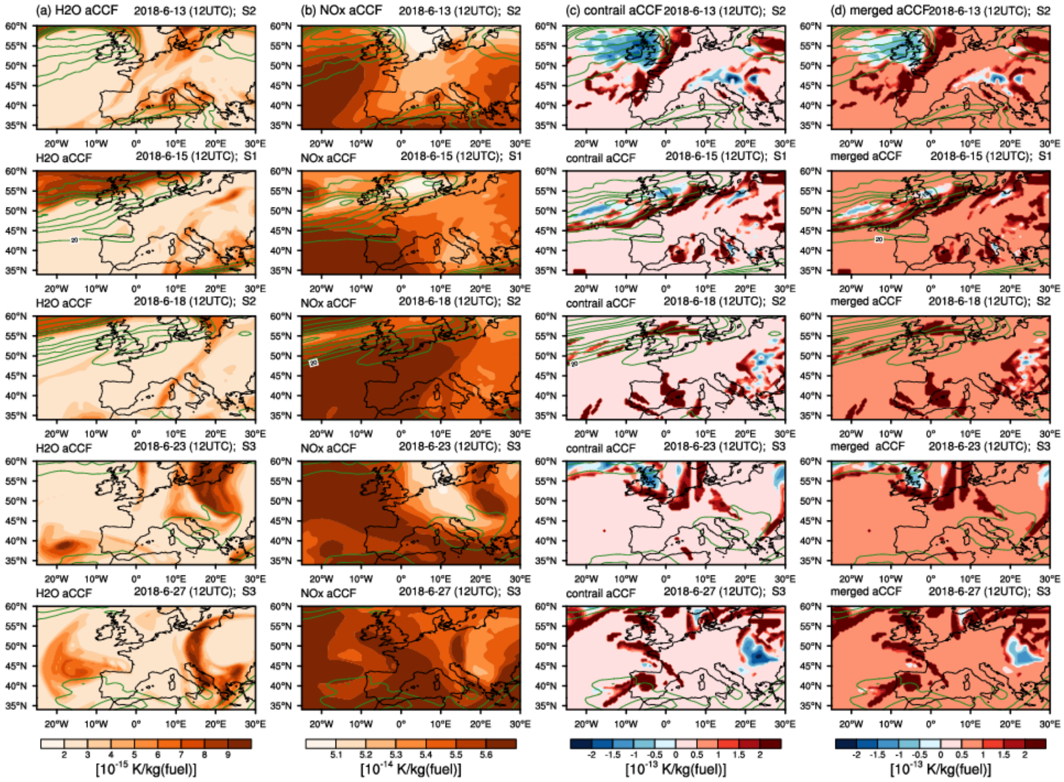

Figure 3: Characteristic patterns of (a) water vapour aCCF [K/kg($_{fuel}$)], (b) NO_x aCCF (including O_3, CH_4 and PMO) [K/kg(fuel)], (c) contrail (daytime) aCCF [K/kg(fuel)], and (d) merged non-CO_2 aCCF [K/kg(fuel)] at pressure level 250 hPa over the European region for five selected days in June 2018 at 12UTC. Individual aCCFs were calculated from ERA5 reanalysis data. Overlaid green lines indicate wind speeds above 30 ms^{-2}.

- Uncertainty in the meteorological forecast was integrated into the ATM system by using an ensemble probabilistic forecast. Based on these robust aCCFs, those weather situations and aircraft trajectories could be identified, which lead to a robust climate impact reduction (for more details see D2.2 [6]).
- A concept to integrate uncertainties, which arise from weather forecast and climate impact prediction, in the overall assessment in order to characterize the robustness of climate optimized trajectories was finalized and applied to the results of WP2 and WP3 [22]. This newly developed concept towards robust aCCFs by integrating uncertainties is described in detail in Section 2.5 of Deliverable D1.2 [3].
- Two flight trajectory optimization tools (TOM and ROOST) calculated climate optimized trajectories following two different approaches: ROOST (robust optimization of structured airspace) by using the TOP 100 routes of the European air traffic and TOM (Trajectory Optimization Module) by using the TOP 10 routes of a representative fictitious route network generated from the European air traffic for different atmospheric conditions in June and December 2018 and investigated the respective mitigation potential.

ROOST is a fast graph-based optimization algorithm capable of determining robust aircraft trajectories in the structured airspace considering meteorological uncertainties applying a stochastical approach. Generally, the aim of the optimization was to find a control policy that minimizes a cost functional while simultaneously satisfying a set of dynamical path and boundary constraints (Figure 4).

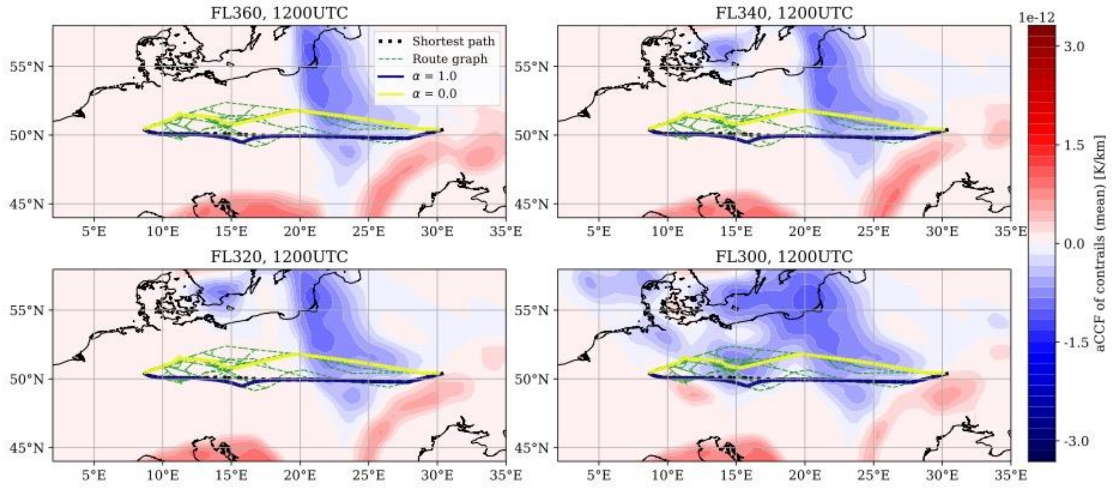

Figure 4: Optimized individual route by ROOST on a day with formation of persistent contrails during daytime. Lateral paths are shown for June 20th 2018,1200 UTC at a variety of flight levels with the colormap indicating the cooling (blue) and warming (red) effects of areas with contrail formation [6].

TOM consist of continuously optimized trajectories (Figure 5). Detailed descriptions of how uncertainties were integrated into both tools can be found in Deliverable D2.1 [4]. All achieved results generated within WP2 can be found in Deliverable D2.2 [6].

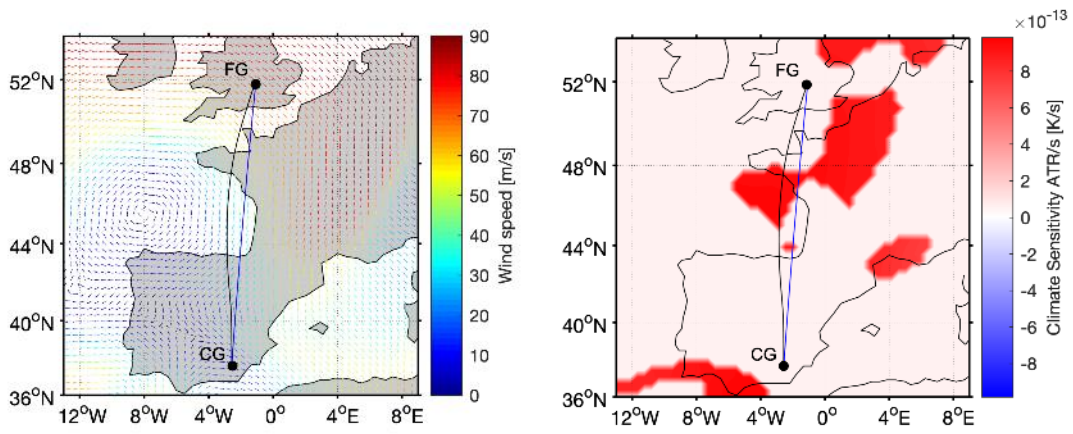

Figure 5: Optimized single route by TOM on June 18th 0000UTC for the most relevant fictitious origin-destination pair by ASK. Both the wind situation (left) as well as the contrail forming areas (right) are shown for an altitude of approximately 11km.

- FlyATM4E implemented a new Multi-Objective Optimization Module, including Decision-Making methods, in the air traffic simulator AirTraf, which is coupled with the ECHAM/MESSy (EMAC) model. Details of these model developments can be found in Section 2.1.3 of D3.2 [9].
- With the EMAC sub-model AirTraf, eco-efficient trajectories were identified under a multitude of weather patterns by decision-making strategies that distribute the cost changes according to the mitigation potential. Figure 6 compares the climate impact of the trajectories selected using different optimization strategies, i.e. optimal Simple Operating Cost (SOC), optimal climate impact (measured in terms of F-ATR20), and eco-efficient trade-offs between the two objectives. Under all the trajectory optimization strategies that were considered, we found that the absolute values of the F-ATR20 from our air traffic sample follow a seasonal cycle, with a higher climate impact during summer than during winter (see Section 3.1.4 of D3.2 [9]).

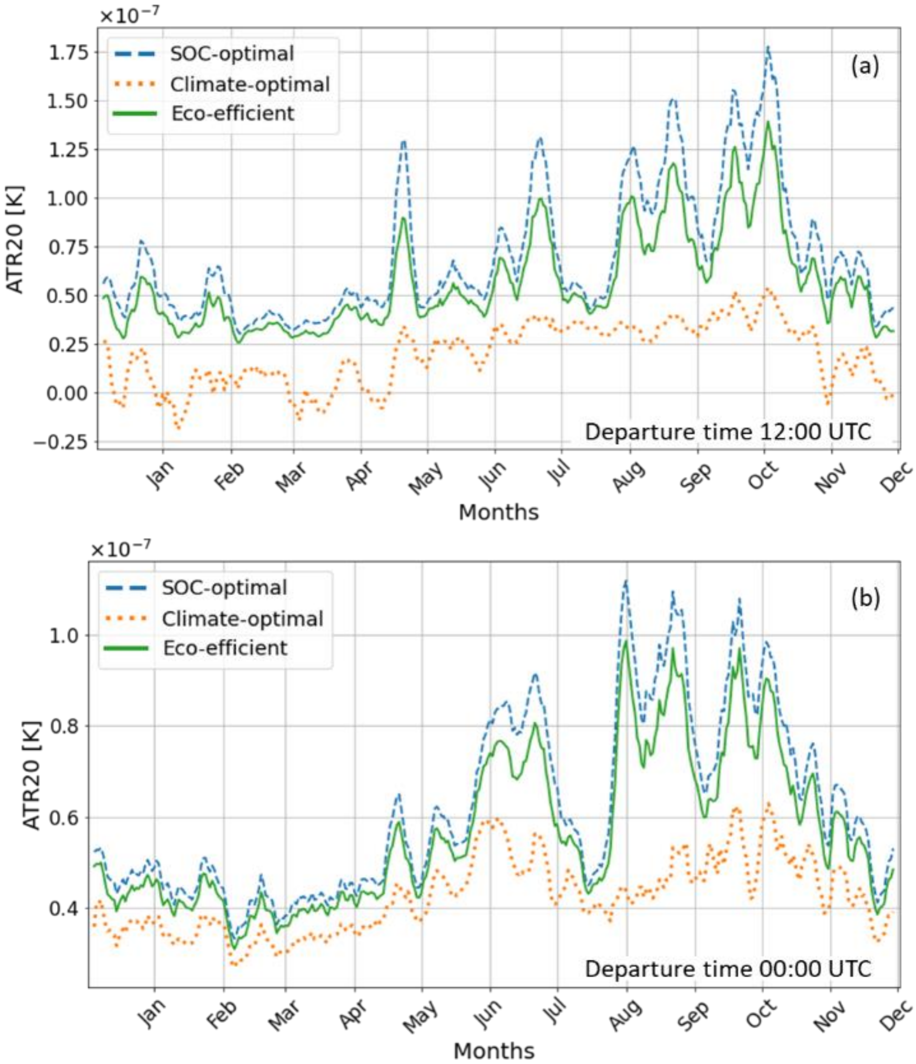

Figure 6: Variability over time of the total F-ATR20 [K] in 2018 from our air traffic sample. Panels (a) and (b) show the results for flights departing at 12:00 UTC and 00:00 UTC, respectively (from D3.2 [9]).

- We employed the AirTraf sub-model to optimize the trajectories including the F-ATR20 in the objective function. Changes in contrail effects provided the largest contribution to the reduction in climate impact on almost every day and night (Section 3.1.3 and Figures 20-21 in D3.2 [9]). NO_x-ozone represented the second most important factor and the changes of climate impact of the other species (H_2O, CO_2) only played a minor role in the overall climate impact reduction potential. However, converting the resulting F-ATR20 values to a different climate metric, we found that the climate impact was also reduced in terms of F-ATR100: therefore, the reduction in short-term climate effects from aviation, such as contrail effects, was also relevant on longer time horizons (Figure 16 in D3.2 [9]).

- By comparing eco-efficient and cost-optimal trajectories, all three models confirmed that the mitigation potential strongly depends on the day of the year and also on the time of the flights (i.e. day-time vs. night-time conditions).
- The analysis of ”win-win” solutions revealed large climate impact reduction potentials between 15% and 80% for the investigated routes and weather situation at zero cost penalty when structured airspace constraints were removed from the optimization. The methodology used to identify ‘’win-win’’ situations is described in Section 2.2 of D3.2, while more details on the results are presented in Section 3.2 of the same report [9].
- High interest of stakeholders was shown on the research topic of FlyATM4E including emphasizing the need to implement mitigation strategies in policy and industry.

In Table 2 we shortly summarize the list of achievements.

Table 2: Overview of main achievements of the individual work packages and related references

	List of achievements	References
WP1	Provision of an improved set of aCCFs Concept for generation of merged aCCFs Technical development of the python Library, that calculates individual and merged aCCFs	Deliverables: D1.1 D1.2 Scientific publications [23], [29]]
WP2	Development of Trajectory Optimization Module (TOM) to consider uncertainties Methodology to include weather related uncertainties in free-route climate optimal flight planning	Deliverables: D2.1 [4] D2.2 [6] Scientific publications [25], [26], [28], [31]
WP3	Development of Multi-Objective Optimization and Decision-Making modules in the EMAC sub-model AirTraf. Implementation of strategy for the identification of eco-efficient trade-offs between climate impact and operating cost. Estimates of mitigation potential of removing structured airspace constraints.	Deliverables: D3.1 [7] D3.2 [9] Scientific publications [24], [27]

2.5 Technical Deliverables

The technical deliverables of FlyATM4E are summarized in Table 3.

Table 3: Technical Project Deliverables. PU = public, CO = confidential. The following table should present and describe all technical deliverables that are included in the GA.

Reference	Title	Delivery Date[1]	Dissemination Level[2]
Description			
D1.1	Technical note on availability of algorithmic climate change functions (aCCFs)	30/07/2021	CO
The objective of this Deliverable is to provide a technical description of algorithmic climate change functions (aCCFs). They represent spatially and temporally resolved information on the climate impact in terms of future temperature changes of aviation emissions at a given time and location in the atmosphere. They include CO_2 and non-CO_2 effects, comprising NO_x, H_2O and contrail-cirrus. These aCCFs can be derived from meteorological weather forecast data.			
D1.2	Report on expanded aCCFs including robustness and eco-efficiency aspects	21/11/2022	PU
The objective of this Deliverable is to provide a description of the expanded prototype algorithmic climate change functions (aCCFs), which will be applied in the overall FlyATM4E multi-modelling concept in order to explore the mitigation potential of climate optimized aircraft trajectories (i.e. FlyATM4E work package 2 and 3). aCCFs represent spatially and temporally resolved information on the climate impact in terms of future temperature changes of aviation emissions at a given time and location in the atmosphere. They include CO_2 and non-CO_2 effects, comprising NO_x, water vapour and contrail-cirrus. These aCCFs can be simply derived from meteorological weather forecast data. As these aCCFs are the object of uncertainties from weather forecasts and climate science, here, the described aCCFs also include robustness aspects. For this purpose, a novel concept has been developed on exploring climate-optimization of aircraft trajectories and the robustness of estimated benefits in terms of mitigation of climate effects. This is done by a systematic risk analysis relying on a Monte-Carlo Method. Further, it is shown that by combining the individual aCCFs of water vapour, NO_x and contrail-cirrus, merged non-CO_2 aCCFs can be generated. Technically this is done with an open-source Python Library. Both individual and merged aCCFs patterns were analysed and show the dominating effect of the contrail aCCF in areas where contrails are forming. Further analysing the variability in aCCFs reveals a clear seasonal cycle in NO_x and contrail aCCFs and a strong variability with different synoptical weather situations and cruise altitudes. Results presented in this deliverable contribute to the overall project objective O1, which is to advance concepts to assess the climate impact of ATM operations while integrating an adequate representation of uncertainties, including CO_2, contrails, ozone, methane, and water vapour climate effects, from weather forecast as well as climate science, and provide concepts for climate information enabling eco-efficient aircraft trajectories.			

[1] Delivery date of latest edition

[2] Public or Confidential

D2.1	Report on methodology to include uncertainties and robustness metrics in trajectory optimization and MET data requirements	25/03/2022	CO
This deliverable describes the overall methodology to include uncertainties in climate impact estimates during planning and optimisation of climate-optimised trajectories. A general description of the input data as well as of the trajectory planning and optimisation tools TOM and ROOST is provided. Sources of uncertainty relevant for trajectory optimisation can be associated to numerical studies to calculate climate impact, to research leading to generation of aCCFs and uncertainties in meteorological forecast data. Specific adaptations of the trajectory optimisation models are required to consider uncertainties with respect to meteorology and climate impact and the robustness concept developed in FlyATM4E. Initial results from a case study are presented which also documents the related software implementation steps and provides a definition of the required MET data. Finally, an initial version of the experimental plan is provided as annex.			
D2.2	Report on the assessment of robust eco-efficient trajectories	23/08/2022	PU
This deliverable describes the integration of uncertainties with regard to climate impact modelling into the existing trajectory optimisation tools ROOST and TOM. Specific adaptations of the trajectory optimisation models are required to consider uncertainties with respect to meteorology and climate impact and the robustness concept developed in FlyATM4E. Flight trajectories from the previously selected traffic scenario are optimised taking into account combinations of individual uncertainties. Furthermore, the spread of the mitigation efficiency of these optimised eco-efficient trajectories is estimated. Finally, a robustness assessment is performed based on the results achieved by the optimisations on the basis of exemplary routes and in a consolidated manner for the entire traffic scenario. The achievements documented in this deliverable contribute to the overall project objective O2 on the investigation of aviation's climate impact mitigation potential by developing robust flight planning algorithms through integration of uncertainties from the climate impact analysis and ensemble weather forecasts in ATM.			
D3.1	Report on initial studies on eco-efficient trajectories	30/07/2021	CO
The objective of this Deliverable is to describe the preliminary results obtained within the Work Package 3 (WP3) of the FlyATM4E project towards the identification of eco-efficient aircraft trajectories, i.e., routes leading to a substantial reduction in the aviation climate impact while leaving fuel consumption and operating costs nearly unchanged.			
D3.2	Report on final results on eco-efficient trajectories	19/08/2022	PU
The objective of this Deliverable is to describe the final results obtained within the Work Package 3 (WP3) of the FlyATM4E project towards the identification of eco-efficient aircraft solutions, i.e. trajectories and respective meteorological situations which allow a substantial reduction in climate impact of a flight with low -– or without – penalties in fuel consumption and operating costs. To this end, we further developed the AirTraf and ACCF sub-models, which are coupled with the ECHAM/MESSy Atmospheric Chemistry (EMAC) model. This modelling chain allows us to compute feasible trade-offs between climate impact and aircraft operating costs on yearly time-scale, thus considering the natural variability of atmospheric conditions. In particular, we optimized an air traffic sample of 100 European flights, and we identified trade-off trajectories within the set of Pareto-optimal solutions, which best represent the concept of "eco-efficiency". Moreover, inefficiency in the system were taken into account to identify "win-win" solutions, reducing both cost and climate impact. For this task, we compared the results from ROOST, a model which optimizes trajectories on a structured-airspace (using the current network of Air Traffic Services routes), to the results from TOM, an optimization tool that uses a free-routing airspace (future concept of operations). The achievements documented in this deliverable contribute to the overall project objective O3 on how to identify aircraft trajectories and related weather situations, enabling: (1) "eco-efficient" solutions, which largely			

reduce the climate impact of aviation at almost unchanged costs; or (2) "win-win" situations, which have the potential to reduce both climate impact and operational costs.			
D4.1	Data Management Plan (DMP)	12/11/2021	PU
The objective of this Deliverable is to describe the Data Management Plan (DMP) of FlyATM4E Project. FlyATM4E is included in the pilot under Horizon 2020 called the Open Research Data Pilot (ORD pilot). The Deliverable includes a data summary, including the purpose of data to fulfil FlyATM4E objectives, a description of types and formats of input and output data, the origin, accessibility and approximate size of the data, the re-use of data and their utility for different target audiences. The deliverable also states a plan for continuous update of the document (with versions and content to be updated). FlyATM4E will follow FAIR data principles, and, thus, the deliverable elaborates on a set of guiding principles to make data Findable, Accessible, Interoperable, and Reusable. Allocation of resources to comply with FAIR principles and the data management strategy of FlyATM4E is provided within the document. Last but not least, an analysis on data security, including aspects related to data sharing and data storage is covered in the Deliverable.			
D4.2	Organisation of a Stakeholder Webinar for dissemination of final FlyATM4E results	31/01/2023	PU
The present deliverable details the stakeholder's webinar that FlyATM4E was organized to disseminate the results of the project, targeting key stakeholders. The deliverable lists the objectives of the webinar (framing them into the overall communication, dissemination, and exploitation objectives), including the identification of objectives by the target audience. The deliverable also tackles the stakeholders' engagement and identifies relevant actors (including those already conforming the Advisory Board of the project) that would be potentially targeted to attend the event. Finally, it provides practical information on the date and venue (though it would be a hybrid event), the agenda, and the expected outcomes of the webinar.			
D4.3	Report on recommendations on regarding the implementation of robust and climate impact reducing ATM operations	08/07/2022	PU
This deliverable includes recommendations towards the seamless implementation of climate-optimised aircraft trajectories within the ATM domain. This climate-optimised aircraft trajectories are to enable a robust and eco-efficient reduction in aviation's climate impact. This includes "win-win" solutions based on ATM experts and stakeholder feedbacks. Possibilities of implementation and enablers, but also showstoppers and hurdles are included.			
D4.4	Report on robust and climate impact reducing ATM operations including an overall environmental evaluation and implementation analysis from a hindcast analysis	10/08/2022	PU
This deliverable summarizes the findings from a hindcast analysis applied to a set of trajectories, which are optimized for a given meteorological forecast under uncertainty and evaluated in the presence of actual weather conditions, leading to recommendations for robust and climate impact reducing ATM operations.			
D5.1	Project Management Plan (PMP)	26/10/2020	CO
The main objective of the FlyATM4E project is to expand approved climate impact assessment methods and to identify promising, climate impact reducing aircraft operations. The project will assess the feasibility of a concept for environmental assessment of ATM operations working towards environmental optimisation of air traffic operations. This Project Management Plan (PMP) related to the FlyATM4E project defines how the project is executed, monitored, controlled, and closed. It provides the most up to date and realistic view of the project plan. The content of the PMP can include key messages, communications activities, milestones, channels, and metrics defined with the project partners. The PMP also provides sufficient details on how the next reporting period will be managed. The PMP output is subject to the quality assessment by the SJU. However, these deliverables			

do not appear in the grant agreement as contractual deliverables. The PMP is intended to provide only an update on the project management, and not to repeat all contents provided already in Annex I.			
D5.2	Communication and Dissemination Plan	27/05/2022	PU
The present deliverable details the communication and dissemination plan, including exploitation matters, for FlyATM4E project. It identifies a focal contact for communication purposes. The deliverable includes 4 high-level messages and a short description to be broadcasted in different media with the aim at making the project understandable at a first glance. It states the communication and dissemination goals, which have been disaggregated by target audiences. The deliverable also describes the intended communication, dissemination, and exploitation strategy to reach the established goals. This strategy includes the communication and dissemination means (including the project's website, the social media, targeted conferences and scientific journals), the open-access strategy (including software management strategy), and the strategy to engage different stakeholders. Finally, a detailed communication and dissemination plan of activities is presented, including a schedule and metrics to measure its impact and effectiveness.			
D5.3	Final Project Results Report	03/02/2023	PU
This Report summarizes key findings from the project as well as its key achievements towards the European ATM Master Plan. Furthermore, the project reports on the achieved maturity steps, supported by a self-maturity assessment. The overall objective of the project FlyATM4E was to develop a concept to identify climate-optimised aircraft trajectories in which Air Traffic Management (ATM) can help to provide a robust and eco-efficient reduction in aviation's climate impact and estimate mitigation potential considering CO_2 and non-CO_2 emissions. A systematic analysis of the spatially and temporally resolved climate impact of aviation's emissions was performed by using algorithmic climate change functions for a set of non-CO_2 impacts with a particular focus on identifying sources of uncertainties. Flight trajectory optimization and planning tools were used to explore possibilities in including uncertainties when performing climate-optimized trajectories. The project results highlight that the mitigation potential of flight trajectory optimization shows a large spatial and temporal variability due to the variability of the underlying atmospheric conditions. FlyATM4E contributed to solutions targeting on identifying climate optimized trajectories which provide alternative aircraft trajectories which have a lower climate effect by avoiding those regions of the atmosphere where aviation emissions have a large climate effect, e.g. by forming warming contrails. The project was working towards two solutions. Sol-FlyATM4E-01 is an enabler solution which uses temperature, relative humidity, outgoing longwave radiation and geopotential in order to calculate climate effects of aviation emissions at a given location and time. The solution Sol-FlyATM4E-02 describes the necessary extension of aircraft trajectory planning processes to implement a well-informed and robust multi-objective flight planning with the goal to consider the total climate impact (CO_2 and non-CO_2 effects). The algorithmic climate change functions as defined per Sol-FlyATM4E-01 serve as an enabler for this solution.			

2.6 Key Communication, Dissemination and Exploitation achievements

The FlyATM4E project and project results were presented to the public, industry, science and other stakeholders, for example (links to the events given in the sections below):

- the FlyATM4E project communicated its activities in more than 25 conferences, webinars and workshops;
- the FlyATM4E project published 5 project publications, submitted 3 papers and 2 publications are in preparation;

- the FlyATM4E project prepared an oral presentation, a video and 2 posters for the SESAR innovation days (2020, 2021, 2022);
- the FlyATM4E project conducted 3 interviews with project members and prepared 3 newsletters and 1 press release;
- the FlyATM4E project participated in Women's Day 2021, in International Women's and Girls' in Science Day 2022 and in scholar exchange platform 2022
- the FlyATM4E project contributed to several SESAR publications (e.g. Project fiche results brochure, ATC Network Bulletin) and the SESAR Digital Academy in 2021
- the FlyATM4E project coordinated and exchanged with other /met SESAR ER4 projects (e.g. DYNCAT, CREATE, ALARM, SINOPTICA, FMPMET, ISOBAR), collaborating with ALARM ER in order to develop an open source python library
- the FlyATM4E participated in a thematic workshop organized by DG Clima on non-CO_2 effects of aviation, introducing the concept of climate-optimized trajectories
- the FlyATM4E project produced 3 videos and presented them at an international fair;
- the FlyATM4E project participated in the SESAR Digital European Sky Awards and won in the category 'Sustainability'
- the FlyATM4E Stakeholder Workshop in October 2022 (virtual event) with more than 50 participants from industry, science and service providers.

Communication

Communication was done via various channels, such as scientific communication channels, social media and a project website. The latter has 40 posts with a total of 4176 views. The most visited page was the cover story of the paper "A Comprehensive Survey on Climate Optimal Aircraft Trajectory Planning", which reached 156 visits.

In terms of social media communication:

- The FlyATM4E LinkedIn page has 168 followers from more than 20 countries. Most of them were gained in the last year, when 5187 impressions were achieved.
- On Twitter, 68 tweets were posted, gaining 46 followers.

A complete list of communication activities can be found on our project webpage https://flyatm4e.eu/communication-activities/. A selection of events is given below:

- Concept note shared in the web and the media
- EASN conference, link to ACACIA project, 2 Sep 2020
- ER & IR MET and ENV workshop, 1 Oct 2020
- ECATS conference, poster presentation, 13 Oct 2020
- SJU Digital Academy Green and SMART Aviation - Webinar 1, 19 Nov 2020
- Participation in SESAR Innovation Days (SID), 9 Dec 2020: 1 poster
- SJU Digital Academy Green and smart aviation – Webinar 3, 14 Dec 2020
- Participation in the International Women's Day, 8 Mar 2021
- Expert talk at 4th InterFAB, 11 May 2021
- Participation in the SESAR JU 2021 Digital European Sky Awards; winning in category 'Sustainability', 17 Jun 2021
- Participation in SID 2021, 8 Dec 2021: 1 poster and 1 paper presented
- Interview at SESAR e-News, 17 Dec 2021
- Participation and presentation at EGU2022, 23-27 May 2022

- Participation and presentation at AERO2022, 28-30 Mar 2022
- International Women's and Girls' in Science Day Outreach: Interview with Federica Castino
- Participation and presentation at ILA 2022, 22-26 Jun 2022: project video
- FlyATM4E Stakeholder Workshop, 20 Oct 2022.

Dissemination

In terms of dissemination, the FlyATM4E team published five journal papers ([26],[27],[28],[29],[31]) submitted three papers ([23],[24],[25]) and one publication is in preparation ([22]). Additionally, several FlyATM4E deliverables are available for the public (e.g. [3],[6],[9]).

Exploitation

Concerning exploitation, one of the project's key results is the open source Python Library CLIMaCCF, available on Zenodo with the software DOI: 10.5281/zenodo.6977272 (https://github.com/dlr-pa/climaccf/tree/v0.9.0-rc).

Stakeholders' feedback

Stakeholders participated very numerous in the FlyATM4E events and showed a high interest in the project's topic and results, comprising the scientific events, regular meetings with the FlyATM4E Advisory Board and the FlyATM4E open Stakeholders' workshop. Feedback we have received during these events:

- The usage of the project outcome on climate-optimized trajectories is highly desired.
- Comprehensive description of data uncertainty and validation of quantitative estimate are essential components to ensure the reliability of data to be used in trajectory optimisation.
- An expansion of the geographic scope of the currently available prototypes beyond the NAFC and European airspace is required in order to implement climate-optimized trajectories around the globe.

Lessons learned

During the duration of the project, FlyATM4E has identified some lessons learned for CDE:

- Regular exchange and close communication within the project were essential to guarantee a successful common working area, in this highly interdisciplinary research field involving many different disciplines.
- Regular exchange and communication with the FlyATM4E Advisory Board members was very fruitful and helped to identify communication issues and to see the bigger picture on this interdisciplinary research topic of climate-optimised aircraft trajectories.
- The availability of qualified personal was essential for implementing the overall scientific workplan, as well as for communication issues, e.g. for creating attractive layout or posts.
- In general, communication was essential to discuss the project concept and results during the whole duration of the project, combining efficiently many different type of communication formats.

3 Links to SESAR Programme

3.1 Contribution to the ATM Master Plan

The progress and results of the project contributing to solutions, OIs or enablers comprising the level of maturity are described in this section. The basic document for this chapter is [43] defining solutions and enablers.

FlyATM4E has developed two candidate solutions which are targeting on climate-optimisation of aircraft trajectories. Specifically, additional meteorological parameters were used in order to provide input for the new enabler solution Sol-FlyATM4E-01, which uses temperature, relative humidity, outgoing longwave radiation, and geopotential in order to calculate climate effects of aviation emissions at a given location and time (spatially and temporally dependent information). Relying on information provided by this solution, the second solution Sol-FlyATM4E-02 identifies climate-optimized trajectories for aircraft using daily meteorological forecast information in an expanded flight-planning process.

In an earlier exploratory project ATM4E a feasibility study on how to identify climate-optimized trajectories developed an overall modelling chain on how to plan for alternative aircraft trajectories which have a lower overall climate effect. Earlier industrial research work explored concepts of possible integration of climate effects in the overall air transport system, which was done in coordination with information on severe weather impacts as part of PJ18-04b. Main lesson learned was that an overall integration of such climate effect information should take place via interfaces developed for meteorological (MET) information, because of format, as well as spatial and temporal resolution of such data. Hence, solutions and enablers on climate effects and climate-optimisation are seen as a development of new or advanced MET information which improve the quality, consistency and usability of the information in a full 4D trajectory flight. On severe weather one solution on severe weather was developed (PJ18-04b-02) as an information service, providing convective information with spatial and temporal resolution. However, in PJ18-04b regarding contrail formation and persistence only technical notes and validation exercises were developed. Generally speaking, FlyATM4E work is related to METEO enablers which had been defined to provide MET information relevant for en-route (e.g. METEO-5b, METEO-5c, METEO-06b) where ATM-MET system acquiring, generating, assembling and providing MET information to support all actors. The enabler solution Sol-FlyATM4E-01 also provides information relevant for en-route and could be made available to all airspace users. The corresponding MET service is designed in line with meteorological data relying on identical interfaces and formats, and could be integrated as an additional parameter in the numerical weather forecast acquired by flight planning. Making available climate change functions enhances situational awareness and provides additional information with meteorological nowcasts and forecasts to support enhanced decision making for climate-optimized trajectories.

It has to be noted here that current performance indicators in the field of environment are only partially able to describe the total climate effects, as no dedicated calculation method is defined. Hence, we recommend to define and establish a set of novel additional performance indicators which describe the climate effects in a quantitative way, by using physical climate metrics. In order to stimulate such a development, a set of dedicated approaches exists and definitions could be provided.

Table 4: Project Maturity

Code	Name	Project contribution	Maturity at project start	Maturity at project end
Sol-FlyATM4E-01	Increased situational awareness on climate change effects relying on algorithmic climate change functions	Spatially and temporally resolved information on climate effects of aviation emissions enable assessment of non-CO_2 climate effects of aircraft operations. Efficient integration (in flight planning and airspace management) relies on combining algorithmic climate change functions (aCCFs) with operational numerical weather prediction data of key variables and specific aircraft emissions. This solution provides an efficient meteorological (MET) service to inform on the CO_2 and non-CO_2 climate effect of flight operations. This solution provides spatially and temporally resolved data, measured in units of a dedicated climate metric per emission or flight kilometre. This solution targets to enable assessment and optimization of environmental performance of aircraft operations, more specifically the total climate effect comprising CO_2 and NO_x-induced, H_2O-induced and contrail cirrus effects.	V-level / TRL-0	V-level / TRL-1
Sol-FlyATM4E-02	Identifying robust climate-optimized flight planning in trajectory based operations	Aircraft trajectories can be optimized with respect to an objective function comprising both economical (i.e. operating costs) and environmental (climate impact) criteria. This solution describes the necessary extension of aircraft trajectory planning processes to implement a well-informed and robust multi-objective flight planning with the goal to consider the total climate impact (CO_2 and non-CO_2 effects). Robustness with respect to uncertainty in weather forecast is ensured by incorporating numerical ensemble prediction data in the optimization process. Guidance is provided as to how flights with a high climate impact reduction potential can be identified. The algorithmic climate change functions as defined per Sol-FlyATM4E-01 serve as an enabler for this solution.	V-level / pre-TRL-1	V-level / TRL-2 on-going

3.2 Maturity Assessment

The Maturity Assessment of FlyATM4E is shown in Table 4 and given for both solutions SOL-FlyATM4E-01 and SOL-FlyATM4E-02 in Table 5, Table 6 and Table 7, respectively.

3.2.1 SOL-FlyATM4E-01

Table 5 shows the Maturity Assessment Criteria regarding FO-AO (TRL1) for SOL-FlyATM4E-01.

Table 5: SOL-FlyATM4E-01 FO-AO (TRL1) Research Maturity Assessment

ID	Criteria	Satisfaction	Rationale – Link to deliverables - comments
TRL-1.1	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? - Where does the problem lie? - Has the ATM problem/challenge/need(s) been quantified that justify the research done? Note: an initial estimation is sufficient	Achieved	The ATM problem/challenge/need is to facilitate environmental optimized flight operations by an enhanced robust and fast MET information provision (enabler). Studies (such as e.g. projects REACT4C, ATM4E) have demonstrated that with a minimum cost penalty of only a few percent the climate impact of a flight can be reduced in the order of tens of percent. The challenges and potentials are clearly spelled out in scientific papers [22-29,36] as well as throughout the description of climate change functions provided in deliverables of WP1 (D1.1 [1] and D1.2 [3]).
TRL-1.2	Have the solutions (concepts/capabilities/methodologies) under research been defined and described?	Achieved	The concept and development of the aCCFs has been described in project deliverables (ATM4E, FlyATM4E) as well as peer-reviewed scientific publications [28,29]. During FlyATM4E it was extended towards including robustness information for flight planning considering uncertainties. Such a new capability is highly useful as it provides an increased situational awareness to the ATM system, which is required in order to develop the ATM system towards climate-optimization.
TRL-1.3	Have assumptions applicable for the innovative concept/technology been documented?	Achieved	The above mentioned concept is studied in FlyATM4E with respect to its feasibility and mitigation benefit. Different case studies have been conducted which are described in the FlyATM4E Experimental Plan (EP). Project publications [22-29] and the EP lists the underlying assumptions and limitations.

TRL-1.4	Have the research hypothesis been formulated and documented?	Achieved	The research hypotheses/questions are formulated and documented in the FlyATM4E scientific publications [22-29] and Experimental Plan (see above) together with the assumptions and the set-up of the optimization campaigns.
TRL-1.5	Do the obtained results from the fundamental research activities suggest innovative solutions (e.g. concepts/methodologies/capabilities? - What are these new concepts/methodologies/capabilities? - Can they be technically implemented?	Achieved	FlyATM4E demonstrated the principle of the R-aCCFs and that a robust climate-optimized flight planning is generally feasible with it. However, from the lessons learnt it can be concluded that further research has to be carried out in order to successfully implement and operate the proposed solution: Extensive validation of the aCCFs has to take place in a systematic and comprehensive manner. The aim should be to improve accuracy, validity and robustness of the MET data to ensure an efficient handling during flight planning.
TRL-1.6	Have the potential strengths and benefits of the solution identified and assessed? - Qualitative assessment on potential benefits. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it should be used.	Achieved	The potential benefits of the FlyATM4E solution are large, however further research and development are required to make it available on an operational basis. Depending on the actual weather situation in Europe, a high reduction of total climate impact reduction can be achieved [e.g. 28,29]. The solution is supposed to be mainly used in an aircraft operator's environment, especially for flight planning and dispatching, throughout the different phases of the planning process. It will efficiently help to assess and reduce the total climate impact of flight operations and therefore directly contributes to benefit in environmental performance [22].
TRL-1.7	Have the potential limitations, weaknesses and constraints of the solution under research been identified and assessed? - The solution under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others. - Qualitative assessment on potential limitations. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it may be used.	Achieved	The FlyATM4E solution relies on having (robust) aCCFs available. Existing prototypic algorithms of which have been derived for the North Atlantic Flight Corridor for a set of archetypical summer and winter conditions, only. Their validity towards an application in the European airspace as well as their temporal scope is therefore currently limited and needs further research.

TRL-1.8	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM MP Level?	Achieved	FlyATM4E contributes to reaching the performance ambitions in the key performance area "Environment" of the ATM Masterplan. While the target is to achieve a 5-10% reduction in the gate-to-gate CO_2 emissions, climate-optimized flight planning aims at reducing the overall climate impact including both the effects of CO_2 emissions and non-CO_2 effects. In fact, in many cases CO_2 emissions increase due to climate-optimized flight planning. However, if CO_2 equivalent emissions are relevant, the FlyATM4E solution will even exceed the ambitions.
TRL-1.9	Have stakeholders been identified, consulted and involved in the assessment of the results?. Has their feedback been documented in project deliverables? Have stakeholders shown their interest on the proposed solution?	Achieved	The stakeholder interest in the project is generally very high, and regular stakeholder presentations were performed (e.g. SJU Digital Academy, Fabec Talk, ILA). FlyATM4E has established an Advisory Board (AB) consisting of representatives from all relevant stakeholders, such as e.g. aircraft operators, manufacturers and flight planning services. Regular exchange with the AB takes place and allows for collecting feedback from the potential user community. The advises from the AB members are well documented in the minutes of meeting of the AB meetings and -where applicable- are considered in individual deliverables.
TRL-1.10	Have initial scientific observations been communicated and disseminated (e.g. technical reports/journals/conference papers)?	Achieved	FlyATM4E does research on robust Algorithmic Climate Change Functions, R-aCCFs, which serve as an enabler for the above-mentioned robust climate-optimized flight planning. The concept of the R-aCCFs has been described in detail in D1.1 [1], D1.2 [2] and [22,23].
TRL-1.11	Are recommendations for further scientific research documented?	Achieved	The recommendations for further research are documented in the FlyATM4E scientific publications [22-29] and in the Final Project Results Report [20] in section 4.3.

3.2.2 SOL-FlyATM4E-02

Table 6 shows the Maturity Assessment Criteria regarding FO-AO (TRL1) for SOL-FlyATM4E-02 and Table 7 regarding AO-IR (TRL2).

Table 6: SOL-FlyATM4E-02 FO-AO (TRL1) Research Maturity Assessment

ID	Criteria	Satisfaction	Rationale – Link to deliverables - comments
TRL-1.1	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? - Where does the problem lie? - Has the ATM problem/challenge/need(s) been quantified that justify the research done? Note: an initial estimation is sufficient	Achieved	The ATM problem/challenge/need is to facilitate environmental optimized flight operations by an efficient flight planning methodology that makes use of the innovative MET data to determine robust climate-optimized flight plans. Studies (such as e.g. projects REACT4C, ATM4E) have demonstrated that with a minimum cost penalty of only a few percent the climate impact of a flight can be reduced in the order of tens of percent. The challenges and potentials are clearly spelled out in the proposal as well as throughout the deliverables of WP2 (D2.1 [4] and D2.2 [6]) and WP3 (D3.1 [7] and D3.2 [9]).
TRL-1.2	Have the solutions (concepts/capabilities/methodologies) under research been defined and described?	Achieved	FlyATM4E does research on a methodology to compute robust climate-optimized trajectories using R-aCCFs has been defined. This methodology, which is realized by three different trajectory optimization algorithms (TOM, ROOST, EMAC/AirTraf) is investigated comprehensively in FlyATM4E. All models use weather forecast data from Ensemble Prediction Systems to consider uncertainty in the weather conditions and to obtain a robust solution. The respective descriptions are provided in deliverables D2.1 [4], D2.2 [6] and D3.1 [7].
TRL-1.3	Have assumptions applicable for the innovative concept/technology been documented?	Achieved	The above mentioned concept is studied in FlyATM4E with respect to its feasibility and mitigation benefit. Different case studies have been conducted which are described in the FlyATM4E Experimental Plan (EP). The EP lists the underlying assumptions and limitations.
TRL-1.4	Have the research hypothesis been formulated and documented?	Achieved	The research hypotheses/questions are formulated and documented in the FlyATM4E Experimental Plan (see above) together with the assumptions and the set-up of the optimization campaigns.
TRL-1.5	Do the obtained results from the fundamental research activities suggest innovative solutions (e.g. concepts/methodologies/capabilities?	Achieved	From the lessons learnt it can be concluded that further research has to be carried out in order to successfully implement and operate the proposed

	- What are these new concepts/methodologies/capabilities? - Can they be technically implemented?		solution: A sound and meaningful metric to compare resulting robust optimal trajectories is required to fully understand the variability of the resulting flight plans and to better judge their robustness with respect to meteorological uncertainty.
TRL-1.6	Have the potential strengths and benefits of the solution identified and assessed? - Qualitative assessment on potential benefits. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it should be used.	Achieved	The benefits of the FlyATM4E solution assuming that further research and development effort will have been put into it, are enormous. Depending on the actual weather situation in Europe, a high ratio of climate impact reduction and cost increase can be achieved, especially for “Big Hitter” flights. For instance, there are some flights, which go through large contrail forming regions, which have the potential to reduce their climate impact by up to ~80% for a fuel penalty of only ~5%.
TRL-1.7	Have the potential limitations, weaknesses and constraints of the solution under research been identified and assessed? - The solution under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others. - Qualitative assessment on potential limitations. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it may be used.	Achieved	The potential limitations, weaknesses and constraints of the solution were carried out in the course of the experiments in FlyATM4E. Feasibility and usefulness were demonstrated through the different use cases. All results are documented in the corresponding deliverables, D2.2 [6] and D3.2 [9] and the study design is documented in the Experimental Plan.
TRL-1.8	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM MP Level?	Achieved	FlyATM4E contributes to reaching the performance ambitions in the key performance area “Environment” of the ATM Masterplan. While the target is to achieve a 5-10% reduction in the gate-to-gate CO_2 emissions, climate-optimized flight planning aims at reducing the overall climate impact including both the effects of CO_2 emissions and non-CO_2 effects. In fact, in many cases CO_2 emissions increase due to climate-optimized flight planning. However, if CO_2 equivalent emissions are relevant, the FlyATM4E solution will even exceed the ambitions.
TRL-1.9	Have stakeholders been identified, consulted and involved in the	Achieved	FlyATM4E has established an Advisory Board (AB) consisting of representatives

	assessment of the results?. Has their feedback been documented in project deliverables? Have stakeholders shown their interest on the proposed solution?		from all relevant stakeholders, such as e.g. aircraft operators, manufacturers and flight planning services. Regular exchange with the AB takes place and allowed for collecting feedback from the potential user community. A presentation in the SESAR Digital Academy in Dec 2021, a Fabec seminar had been organized in May 2021 and a FlyATM4E stakeholder event in Oct 2022 had been organized, which were well attended showing that the interest in the project is generally very high.
TRL-1.10	Have initial scientific observations been communicated and disseminated (e.g. technical reports/journals/conference papers)?	Achieved	Several communication and dissemination activities have been carried out so far as also described in the respective deliverable. Among those are conference papers and poster presentations providing a conceptual overview on the methodology. Additionally, technical papers are published as well and some more are under preparation right now and to be published in scientific journals soon. Their spectrum ranges from review papers to detailed trajectory optimization publications.
TRL-1.11	Are recommendations for further scientific research documented?	Achieved	The recommendations for further research is documented in the Final Project Results Report [20] in section 4.3.

Table 7: SOL-FlyATM4E-02 AO Research Maturity Assessment

ID	Criteria	Satisfaction	Rationale – Link to deliverables - comments
OPS.ER.1	Has a potential new idea or concept been identified that employs a new scientific fact/principle?	Achieved	The new idea constituting this solution is to combine Ensemble Prediction System (EPS) weather forecast data with the newly developed aCCFs (solution 1, see above) and to integrate this into flight planning (trajectory optimization) algorithms. The concept description is provided in the proposal and in a concept paper.
OPS.ER.2	Have the basic scientific principles underpinning the idea/concept been identified?	Achieved	The underlying scientific principle is the so-called robust trajectory optimization problem. In FlyATM4E this problem is solved in a new way taking into account uncertainty in meteorological data. The

			concept description is provided in the proposal and in a concept paper.
OPS.ER.3	Does the analysis of the "state of the art" show that the new concept / idea / technology fills a need?	Achieved	Flight planning so far was primarily based on monetary objective functions driven by operating costs. However, previous research (e.g. project ATM4E) showed that for a large number of flights high climate impact reductions can be achieved for relatively small cost increases. In order to really implement this and benefit from the potentials, a robust trajectory optimization capability needs to be in place, that is fast and efficient enough to be applied in flight planning. The new concept therefore definitely fulfils an urgent need.
OPS.ER.4	Has the new concept or technology been described with sufficient detail? Does it describe a potentially useful new capability for the ATM system?	Achieved	The concept and development of the robust climate-optimized flight planning capability is described in project deliverables such as D2.1 [4], D2.2 [6], D3.1 [7] and D3.2 [9] as well as peer-reviewed scientific publications. Such a new capability is highly useful as it provides the possibility to the ATM system including surrounding stakeholders (e.g. airlines) to determine robust climate-optimized flight plans.
OPS.ER.5	Are the relevant stakeholders and their expectations identified?	Partial (Non blocking)	FlyATM4E has established an Advisory Board consisting of representatives from all relevant stakeholders, such as e.g. aircraft operators, manufacturers and flight planning services. Regular exchange with the AB takes place and allows for collecting feedback from the potential user community. The interest in the project is generally very high. The advises from the AB members are well documented in the minutes of meeting of the AB meetings and -where applicable- are considered in individual deliverables.
OPS.ER.6	Are there potential (sub)operating environments identified where, if deployed, the concept would bring performance benefits?	Achieved	The solution is supposed to be mainly used in an aircraft operator's environment, especially for flight planning and dispatching. It will efficiently help to reduce the climate impact of flight operations and therefore directly contributes to a benefit in environmental performance. Also in the ATM context, e.g. for the network manager to evaluate flight plans with respect to climate

			impact, a high performance benefit can be expected.
PER.ER.1	Has a feasibility study been performed to confirm the potential feasibility and usefulness of the new concept / idea / Technology being identified?	Achieved	The feasibility study was carried out in the course of the experiments in FlyATM4E. Feasibility and usefulness were demonstrated through the different use cases. All results are documented in the corresponding deliverables, D2.2 [6] and D3.2 [9] and the study design is documented in the Experimental Plan.
PER.ER.2	Is there a documented analysis and description of the benefit and costs mechanisms and associated Influence Factors?	Partial (Non blocking)	The benefit and cost mechanisms and their interactions are shown in the Pareto diagrams, which are provided in the deliverables D2.2 [6] and D3.2 [9].
PER.ER.3	Has an initial cost / benefit assessment been produced?	Partial (Non blocking)	An initial cost / benefit assessment was essential part of the feasibility study (see above). However, not the costs of the tool implementation have been assessed, but the implications on operating costs in the context of flight planning.
PER.ER.4	Have the conceptual safety benefits and risks been identified?	Not Applicable	The safety benefits and risks of the concept have not been quantified. However, as safety is not directly affected by the solution, this was considered out of scope of the analysis.
PER.ER.5	Have the conceptual security risks and benefits been identified?	Not Applicable	The security benefits and risks of the concept have not been quantified. However, as safety is not affected by the solution, this was considered out of scope of the analysis.
PER.ER.6	Have the conceptual environmental impacts been identified?	Achieved	One of the key objectives of the FlyATM4E project was to quantify the climate impact of robust climate-optimal flight planning. This objective has been successfully achieved by the experiments conducted. All results are documented in the respective deliverables.
PER.ER.7	Have the conceptual Human Performance aspects been identified?	Not Applicable	The Human Performance aspects of the concept have not been quantified. However, as the tool is considered to be a substitution for existing flight planning tools, no significant implications to Human Performance are expected.
SYS.ER.1	Has the potential impact of the concept/idea on the target architecture been identified and described?	Partial (Non blocking)	The potential impact of the FlyATM4E concepts on the target architecture was discussed with stakeholders, e.g. availability of advanced MET services to airspace users. An integration of the enabler solution via meteorological

			interfaces is proposed, as information is required for trajectory operations, e.g. by ANSPs, ATC, possibly EUROCONTROL.
SYS.ER.2	Have automation needs e.g. tools required to support the concept/idea been identified and described?	Achieved	The solution itself constitutes a methodology that is already implemented in the tools TOM and ROOST. These tools provide the necessary level of automation that is required for the solution. However, they are currently used for research purposes only and not operationally applied.
SYS.ER.3	Have initial functional requirements been documented?	Achieved	Functional requirements for the solution were described in D1.2 [3], e.g. when describing spatial and temporal resolution of the proposed MET Service, as well as in the FlyATM4E Experimental Plan.
TRA.ER.1	Are there recommendations proposed for completing V1 (TRL-2)?	Achieved	In section 4.3 of the Final Project Results Report (D5.3 [20]), dedicated recommendations on future implementation steps have been given in order to achieve a higher TRL.
VAL.ER.1	Are the relevant R&D needs identified and documented? Note: R&D needs state major questions and open issues to be addressed during the development, verification and validation of a SESAR Solution. They justify the need to continue research on a given SESAR Solution once Exploratory Research activities have been completed, and the definition of validation exercises and validation objectives in following maturity phases.	Not achieved	-

4 Conclusion and Lessons Learned

4.1 Conclusions

Finally, this section summarizes the main conclusions based on the results and links to the evidence collected during the project. On the usage of merged aCCFs V1.1 to characterize aviation's climate impact (linked to O1 (see 2.2)):

- The enhanced MET service based on the aCCFs V1.1 (including the newly introduced educated guess factors) is in line with the state-of-the-art understanding of aviation's climate impact and provides information on the CO_2 and non-CO_2 climate effects for airspace users in flight planning. Indeed, the merged non-CO_2 aCCFs V1.1 describe the overall climate impact of aviation's non-CO_2 emissions by considering technical specifications of e.g., aircraft type and physical climate metric.
- The newly developed Python Library based on the merged aCCFs V1.1 allows an open and convenient implementation of the aCCFs' formulas in the air traffic simulation environment and provides a direct link between non-CO_2 climate effects to fuel consumption as a common assessment indicator.

On the obtention of eco-efficient and climate optimal trajectories (linked to O2, first three bullet points (see 2.2), and O3, bullet points 4 and 5 (see 2.2)):

- Merged aCCFs have been successfully integrated in different types of trajectory generators (TOM, ROOST, EMAC/AirTraf), all of them capable of finding optimal trajectories that weight cost and climate.
- The robustness analysis using ensemble probabilistic forecast showed that mitigation potentials vary due to the variability of atmospheric conditions and the uncertainty in weather forecast could be addressed by incorporating the numerical ensemble data while implementing the aCCFs. Ensemble data from probabilistic weather forecast allowed identifying robustness of mitigation potential of alternative trajectory solutions. It has been shown that the climate effects of contrails are highly uncertain.
- The climate-optimized flight trajectories using different flight trajectory optimization tools (TOM, ROOST, and EMAC/AirTraf) showed a consistent seasonal pattern of climate mitigation potential (higher in winter than in summer), which provided evidence to the air space users where large mitigation gains could be expected.
- Eco-efficient solutions do exist and could be identified. Using the EMAC/AirTraf optimizer on the top 100 routes for different days and seasons had systematically shown eco-efficient solutions, i.e. high climate mitigation gains at relatively low costs. These aggregated results have also been analysed in terms of seasonality (higher climate impact during summer than during winter); contribution of the different species (contrails are dominant); sensitivity to the time horizon (mitigation potential is also present).
- „Win-Win" solutions do exist and could be identified. In FlyATM4E, "win-win" solutions were determined by comparing the optimisation results of ROOST (structured airspace, which mimics the current network of ATS routes relying on DDR2 data) and TOM (continuous optimization on a full 3D free routing airspace). "Win-win" solutions have been identified for nine investigated routes, which reflected the inefficiencies caused by the route structure (not differentiated between horizontal and vertical inefficiencies).

We have also assessed how large the climate impact mitigation potential of climate-optimised flight planning in Europe could be considering meteorological variability and uncertainty:

- Using the EMAC/AirTraf optimizer on the top 100 routes (and a wide variety of days), we found climate mitigation potentials (F-ATR20) of about 20% with a 0.5% increase in operational cost in day-time flights (10% mitigation at night).
- Using the ROOST optimizer (that considers structured airspaces) on the top 100 routes (and a wide variety of days), we found that the mitigation potentials are highly variable due to changes in atmospheric conditions. For the considered case studies, in general, the night-time flights resulted in a higher reduction of climate impact (20-50%) compared to daytime (20-30%). Overall, a maximum 3% increase in standard operational costs could reduce the climate impact by 20-50%. Allowing a 0.5% cost increase, the mitigation potential varied by 10-30% at night and 10-20% during day.
- Using the TOM optimizer (that considers free routing airspaces) on the top 10 routes (and a wide variety of days), the mitigation potential was around 40% compared to a 2% cost increase.
- In the case of win-win situations, by comparing solutions to ROOST and TOM at the reference cost level (i.e., same cost), the climate impact could be reduced between 15% and up to 80% on the investigated routes.

Even though we do not know (because it is market-driven) what would be an acceptable trade-off between costs and climate impact reduction, we provide Pareto-optimal solutions that allow to analyse the whole set of possible solutions.

4.2 Technical Lessons Learned

Several models, methods and techniques have been applied in the course of the project. In this section, the technical lessons learned are described, that can also be seen as a starting point for related projects.

- Temporal and spatial resolution of numerical weather prediction (NWP) data determines the resolution of the aCCFs. Horizontal resolution of NWP data requires tuning of key MET input parameters and a relative humidity threshold for ice supersaturated regions (ISSR) (WP1).
- A kind of closure experiment compared quantitative estimates of climate effects with the climate response model AirClim assuring consistency with scientific results from other assessment papers (e.g. when comparing with climatological estimates) (WP1). Based on this closure experiment, an improved set of aCCFs was provided. For more details see Section 2.2 of Deliverable D1.2 [3].
- The temporal resolution of the meteorological data differs between the trajectory optimizers and the global climate model as, in the first case, a discrete temporal resolution is used, while in the global chemistry climate model, instantaneous weather data is available. Interpolation of NWP data between those discrete points in time is not recommended as averaging of individual meteorological fields might result in physical inconsistency of the resulting situation (WP1).
- If the optimizer needs gradients in order to identify a solution (convergence towards a solution), an interpolation of the aCCF fields might be required (WP2).

- FlyATM4E developed an open-source Python Library, that efficiently calculates both the individual aCCFs and the merged non-CO_2 aCCFs. The merged aCCFs can only be constructed with the technical specification of the emission indices of the selected engine/aircraft type.
- For a systemic approach to trajectory optimization, which considers the mitigation potential of the whole air traffic sample and only optimizes with respect to their climate impact, the fraction of the flights with the largest potential reduction in ATR20 can limit cost penalties more than single-flight optimization. This can be taken into account in the future using 'a priori' information (e.g. target absolute reduction in climate impact, determined from the results of this project) as input for the optimization tool AirTraf (WP3).

FlyATM4E also identified some non-technical lesson learned:

- Regular Work-Package specific meetings (e.g. WP2 & WP3) were necessary for communication within the team. Moreover, one-to-one exchanges for consistency of data usage and/or format of results and deliverables was required.
- A unified platform (project team site) for files and reports with access for all partners simplified the general exchange, meetings and reporting progress of deliverables, as well as the dissemination since all data was online accessible for all partners in a structured manner.

4.3 Plan for next R&D phase (Next steps)

The developed results and concepts reached and developed in FlyATM4E are very promising, but still give room for further research that should be carried out in the future to continue this R&D endeavour. Briefly, the next steps are described in this section.

Towards exploratory research

Basic research is required on relationships which will lead to the definition of updated and extended algorithmic climate change functions for other seasons and regions of the atmosphere, in order to expand geographic and temporal scope of aCCF prototypes, but also for other remaining non-CO_2 effects. Such work requires state-of-the-art climate chemistry modelling comprising modelling of climate effects, in close collaboration with international assessment activities.

- Provide a definition of an adequate physical climate metric which is able to assess (quantify) climate effects of future emissions (and not of historic emissions as done in the radiative forcing concept) by e.g. evaluating atmospheric response (temperature change) after a dedicated time horizon (e.g. 20, 50, and 100 years).

- Perform a systematic comparison of different approaches and concepts on how to provide on an operational basis such a dedicated MET service. Such a MET service should contain spatially and temporally resolved information on climate effects induced by aviation emissions. Such scientific work comprises to evaluate radiative transfer modelling which determines climate effects of aviation emissions, as well as to assess empirical models of contrail life cycle and comprehensive chemistry-climate modelling involving representation of reactive species and aerosols which influence radiative transfer in the atmosphere. This will give the basis for developing an enabler solution targeting at a higher TRL.

- Compare the current quality of meteorological forecasts, as well as of individual approaches presented so far in order to provide a quantitative measure of the climate effects of aviation emissions, comprising contrail (cirrus) effects, NO_x-induced effects, direct effects of water vapour emissions and aerosol induced effects. Here, characterizing the performance skills of the meteorological forecast (e.g. comprising upper tropospheric atmospheric humidity data) informs the advanced MET service (described above) on the reliability of the identified atmospheric fields.

- Improve and systematically evaluate the quality of the weather forecast (performance skill) to represent those key meteorological fields which are relevant for climate effects of aircraft emissions, e.g. upper tropospheric humidity, ice water content or representation of ISSR, as well as background concentration of reactive species.

- Explore possible options to evaluate and validate contrail formation and atmospheric conditions, by e.g. satellite products. This will allow to gain confidence in radiative effects induced, but also identify success of alternative routing strategies which aim, e.g. to avoid warming contrails as could be explored during live trials.

- Investigate relationship between atmospheric conditions at time of emission and subsequent non-CO_2 climate effects towards development of extended aCCFs. From a conceptual point of view, similar methods developed for contrail, NOx-induced and water vapour effects could be applied for development of aCCFs for all other remaining non-CO_2 effects, once advanced scientific knowledge is available.

- A systematic assessment of climate effects for individual synoptic situations using state-of-the art chemistry climate models could inform airspace users and help to develop strategies for identifying those days at which non-CO_2 effects play an important role. This results in a large climate effect mitigation potential by reducing these non-CO_2 effects, e.g. in identifying and characterizing those days (and synoptic situations, e.g. described by atmospheric indices) at which strong warming contrails form or ozone is produced efficiently and in developing strategies how to best avoid such regions with large effects.

- One of the challenges when implementing climate-optimized trajectories lies in the automatization of the workflow, which requires methodologies for assessing trajectory performance and robustness. Therefor adequate methodology (e.g. based on curve similarity analogy) to compare different trajectories with respect to their similarity needs to be developed. This will add an additional dimension to the robustness evaluation and help to understand the relationships between a variability in the weather forecast and the corresponding optimum flight plans.

Towards industrial research

Having developed enablers and solutions within FlyATM4E now enables airspace users to explore usability and gain experience in using while proposing further developments, e.g. temporal and spatial resolution, representation of information. Further research is needed to elaborate identified solutions and to bring them to higher TRL and future implementation.

- Implement prototypes of algorithmic climate change functions in various state-of-the-art trajectory-planning tools, in order to explore both expansion of mathematical cost-functions in the optimisation and integration of aCCFs fields in existing architecture and infrastructure.

From a conceptual point of view the enabler solution developed could be implemented in different phases of the flight planning process, comprising strategic and tactical flight planning.

- Evaluate if current operational trajectory planning tools and systems can be enabled to avoid regions with large climate effects in order to mitigate total climate effect of aviation when working towards sustainable aviation. Particular focus should be given on identifying requirements and recommendations on requirements, e.g. concerning a dedicated MET service, as well as documenting current limitations and defining future developments which are required to enable climate-optimized trajectory optimization.

Towards policy support

Formulate requirements on how the quantitative assessment of climate effects could be implemented as one element in the air transport system comprising an expanded emission trading scheme, as one central point is to be able to account for benefits of the alternative, climate-optimised trajectory (in order to create incentives).

- Explore solutions identified in FlyATM4E to identify how current operational systems would need to be expanded or adapted in order to work towards environmental assessment of climate effects and future implementation (and enabling) of climate optimized aircraft routing, e.g. in the European Airspace.

5 References

5.1 Project Deliverables

[1] FlyATM4E, Technical note on availability of algorithmic climate change functions (aCCFs), D1.1, 00.01.00, 30/07/2021

[2] FlyATM4E, Draft Report on expanded aCCFs including robustness and eco-efficiency aspects, D1.2.010, 00.01.00, 31/03/2022

[3] FlyATM4E, Report on expanded aCCFs including robustness and eco-efficiency aspects, D1.2, 00.04.00, 21/11/2022 (download)

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[5] FlyATM4E, Draft Report on the assessment of robust eco-efficient trajectories, D2.2.010, 00.01.00, 29/04/2022

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Appendix A

A.1 Glossary of terms

Term	Definition	Source of the definition
AIR-REPORT	A report from an aircraft in flight prepared in conformity with requirements for position, and operational and/or meteorological reporting.	ICAO Annex 3
Eco-efficient	Flights that reduce climate impact significantly with little or no influence on cost	Proposed by FlyATM4E
METEO	Code used in ATM Master Plan for a group of enablers	ATM Master Plan
Win-win	Flights that reduce both climate impact and cost when considering operational inefficiency	Proposed by FlyATM4E

Table 8: Glossary

A.2 Acronyms and Terminology

Term	Definition
AB	Advisory Board
ACARE	Advisory Council for Aeronautics Research in Europe
aCCF	Algorithmic climate change function
AirTraf	Air Traffic Simulator
ATM	Air Traffic Management
CDE	Communication, Dissemination and Exploitation
CO	Confidential
CO_2	Carbon Dioxide
D	Deliverable
DMP	Data Management Plan
EPS	Ensemble prediction system
FlyATM4E	Flying Air Traffic Management for the Benefit of Environment and Climate
GPU	Graphics processing unit
H_2O	Water vapour

ISSR	ice supersaturated regions
MET	Meteorological
MS	Milestone
NO_x	Nitrogen Oxide
NWP	Numerical weather prediction
O_3	Ozone
ORD	Open Research Data
POPD	Protection of Personal Data
PMO	Primary Mode Ozone
PMP	Project Management Plan
PU	Public
R-aCCF	Robust algorithmic climate change function
R&D	Research and development
ROOST	Robust optimization of structure airspace
SESAR	Single European Sky ATM Research Programme
SWIM	System Wide Information Management
S3JU	SESAR3 Joint Undertaking (Agency of the European Commission)
TOM	Trajectory Optimization Module
WP	Work package

Table 9: Acronyms and technology

Appendix B Experimental Plan

This appendix contains the final version of the FlyATM4E Experimental Plan ("EP").

In SESAR projects, such a plan is usually named „Validation Plan" for the Industrial Research projects and „Demo Plan" for the Very Large Demonstrator projects. As recommended in the Experimental Approach Guidance document, for Exploratory Research projects the term „Experimental Plan" is appropriate. We will therefore use this term in FlyATM4E.

B.1 Purpose of Experimental Plan

The purpose of the FlyATM4E EP is to secure scientific best practices while ensuring that all key aspects are considered during the design and execution of the FlyATM4E experiments.

No contractual deliverable for the EP was planned during grant agreement preparation, but it has been agreed, that an intermediate version of the EP shall be created, which was already delivered as annex of D2.1 (due M17) as a living document. Hereby, the final version is submitted as annex of the Final Project Results Report (D5.3). The work on the EP started early in the project and the document has been continuously refined throughout the project.

B.2 Definition of experiments in project's context

Obviously, the description of experiments is at the heart of this document. Therefore, it is reasonable to start with a definition of the term "experiment" in the project's context.

According to Wikipedia, an experiment is a procedure carried out to support or refute a hypothesis. Experiments provide insight into cause-and-effect by demonstrating what outcome occurs when a particular factor is manipulated. Experiments vary greatly in goal and scale but always rely on repeatable procedure and logical analysis of the results. In engineering and the physical sciences, experiments are a primary component of the scientific method. They are used to test theories and hypotheses about how physical processes work under particular conditions.

Based on that, „Experiments" in the FlyATM4E context shall be considered numerical experiments for answering the following research questions reflecting the project's overall objective:

- How can climate-optimised aircraft trajectories be planned, that support ATM in providing a robust and eco-efficient reduction in aviation's climate impact?
- How large is the mitigation potential, taking into account CO_2 and non-CO_2 emissions through meteorological data, ensemble prediction and eco-efficient trajectories?

The experiments will be carried out in the course of the technical work packages WP1, WP2 and WP3. While WP1 provides the conceptual and algorithmic basis, in WP2 and WP3 this will be tested and applied within numerical simulations and optimisation runs. The corresponding methodologies as well as findings are therefore documented in the respective deliverables D2.1, D2.2, D3.1 and D3.2.

B.3 Characteristics of the experiments

The characteristics of the experiments in FlyATM4E can be described as follows:

The experiments are of **numerical** nature leading to **quantitative results** that not only allow for the judgement whether a certain solution, e.g. trajectory, is superior over another, but also how much they differ with respect to certain metrics.

Some of the results are used to create **Pareto fronts** that enable the **trade-off** of two usually conflicting variables. Those curves show how much one parameter is penalized, if the other is improved. In FlyATM4E, trade-offs between costs and climate impact reductions (**KPAs cost-effectiveness and environment**) are foreseen, while costs shall be measured in a simplified way.

As typical for scientific projects, the **validation** of the experiments will be done in three different ways: by (1) comparison with existing literature, by (2) comparison of different tools with different fidelity levels, and by (3) interpretation based on well-established scientific knowledge.

B.4 Research questions and hypotheses

Experiments in FlyATM4E are carried out to answer research questions and test certain hypotheses. Key questions and hypotheses identified so far are:

(RH/1) Ensemble data from probabilistic weather forecast allows to identify robustness of mitigation potential of alternative trajectory solutions.

(RH/2) „Cherry-picking“ (also known as “eco-efficient”) solutions do exist and can be identified.

(RQ/3) How large is the climate impact mitigation potential of climate-optimised flight planning in Europe considering meteorological variability and uncertainty?

(RQ/4) What would be an acceptable (eco-efficient) trade-off between costs and climate impact reduction (on a single mission basis / on average)?

(RH/5) There is room for improvement in the European ATS route network to exploit the full potential of climate-optimised flight planning (unconstrained free-flight vs. constrained graph-based).

B.5 Approach

Within the experiments in FlyATM4E, independent, dependent and control variables are used. Dependent variables are those which are studied under the supposition or demand that they depend by some rule on the values of other variables. In contrast to that, any variable that the experimenter manipulates can be called an independent variable. In addition, control variables are used to control the dependent or independent variable, while not being the focus of the experiment itself.

In FlyATM4E, the flight plan representing the air traffic sample to be optimised as well as the corresponding aircraft types and also the weather data can be considered **control variables**.

The weighting factor for trading climate impact against cost influences the optimiser’s cost functional and therefore serves as an **independent variable**, while the resulting optimised trajectory is affected. The trajectories and the Pareto front resulting from a number of runs with different weighting factors, hence, are the **dependent variables**.

Overall, the experiments are set up such that they are fully **reproducible**. Both **deterministic and stochastic approaches** are applied (see also description of methodology in this deliverable). **Sensitivity studies** are performed to understand how certain assumptions in the control variables influence the experiment’s outcome. As the investigation of robustness is a main objective in FlyATM4E, the

consideration of uncertainties both in terms of meteorology (weather forecast) and in terms of level of scientific understanding (LOSU) of the climate impact is a key element in the experiments.

It is noticed, that the investigated weather situations may have a large impact on the results, e.g. contrail scenario. Therefore, the experiments are planned such that a sufficient number of days with different weather situations are considered and the weather **variability is captured** in the studies.

Generally, **different scenarios** are studied in FlyATM4E: The **Business-as-usual** (BAU) scenario reflects current flight planning practices and allows for reproducing flight trajectories from real historical flights to serve as a reference. Then, the **minimum-cost scenario**, which is assumed to be close to the BAU constitutes one extreme case and the initial point along the Pareto front. It results, if the cost functional of the optimiser purely minimizes costs and ignores any other effects. In contrast to that, there is the **minimum-climate impact scenario** representing the other extreme case and the end point along the Pareto front. It results, if the cost functional of the optimiser only considers climate impact effects. Between those two points the Pareto front contains all possible **Pareto solutions**.

With respect to the **external validity** of the results, it should be noted, that in order to transfer the results to an operational environment, an increased LOSU would be required which may lead to an increased acceptance. Also, political regulations and/or monetary incentives would be required.

The experiments in FlyATM4E are carried out in a certain **sequence** to ensure e.g. submodel validity before scaling up to the entire scope of the air traffic scenario. This means that before the methodology is applied to a large-scale scenario individual routes are investigated. The cherry-picking methods are tested offline before they are implemented to the complex model.

The experiments conducted in FlyATM4E are **model-based, fast-time simulation** exercises. Neither **emergent behaviour** will be assessed with the set-up, nor are **rare events simulations** carried out. Also, no **human-in-the-loop simulations** are required, no **field studies**, **shadow-mode trials** or **observations** and no **questionnaires** are necessary to fulfil the tasks defined in FlyATM4E.

B.6 Case studies in FlyATM4E

In FlyATM4E, three different use cases are studied in detail. Those are the robust solutions under meteorological uncertainties (subject of WP2), “Eco-efficient solutions” (“Cherry-picking” situations) and “Win/win situations” (subject of WP3). Those case studies target different research questions/hypotheses (see above) and therefore differ with respect to the requirements to the input data or the temporal scope of the study.

B.6.1 Air traffic sample selection

To define the requirements for the air traffic sample selection in FlyATM4E a virtual workshop was conducted in November 2020.

With creative techniques (brainstorming), ideas were collected about what is relevant and needs to be considered in the definition of the case studies.

Figure 1 shows the results of the brainstorming session. From that the following conclusions, which influence the case studies in FlyATM4E, were taken:

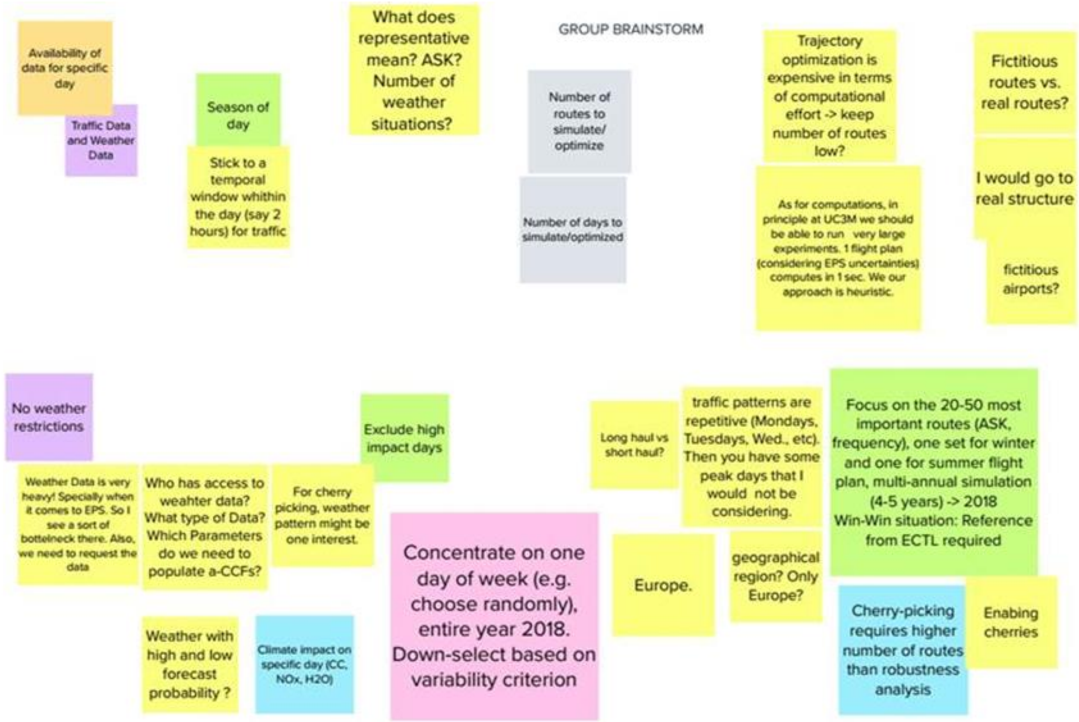

Figure 7: Results of brainstorming session during air traffic sample requirements workshop (13 Nov 2020)

- The optimisation method at UC3M (graph based) is fast, computation time therefore not critical; for optimal control approach (TUHH) computation time can be a showstopper. -> Reduction of complexity might be reasonable;
- EUROCONTROL's Demand Data Repository (DDR2) is no longer available (data downloaded earlier can still be used). However, the EUROCONTROL R&D database provides large datasets for months March, June, September and December from 2015 onwards up to 2018;
- In contrast to ATM4E, in FlyATM4e we will focus on a low number of routes (10, 20-50, 100) but consider variety of weather cases (significant number of days);
- The use of fictitious or artificial cluster routes has been proposed to simplify the problem, while still considering more flights;
- We will focus on Europe geographically (intra-ECAC more precisely);
- The requirements for the robustness study differ from those for cherry-picking study -> Split up data sample based on case study;
- Cherry-picking requires higher number of routes than robustness analysis;
- Traffic will be selected based on the analysis of 2018 data from Sabre Market Intelligence; most ASK-contributing flights to be selected, both for a summer and a winter flight schedule;
- Due to the ensemble forecast the weather data will quickly become voluminous; so, the number of days (especially for robustness study) needs to be reasonably reduced;

- For the Win-Win case study point profile data from EUROCONTROL are required as a reference; if data is not available the method from Madrid can be used to artificially create reference routes;

Mid 2021 another virtual workshop was conducted to select the study days given the fact that a limited number of days should be processed.

The objective of this selection exercise was to identify a sufficient number of days with weather variability to demonstrate the FlyATM4E concept feasibility for different weather situations. This selection should be subject to some constraints. Those were

- Avoid days with high number of weather regulations, as these would impede the traffic situation and affect the analysis (convection activity)
- Consider data availability for traffic and meteorology data
- Set a maximum number of days to limit computational effort

From that it was concluded that the selection rule would be to focus on the months Mar-Jun-Sep-Dec 2018, as they are available in the EUROCONTROL R&D Archive, and to pick 5 homogeneously distributed days (5-10-15-20-25) per month with less than 20 weather regulations per day.

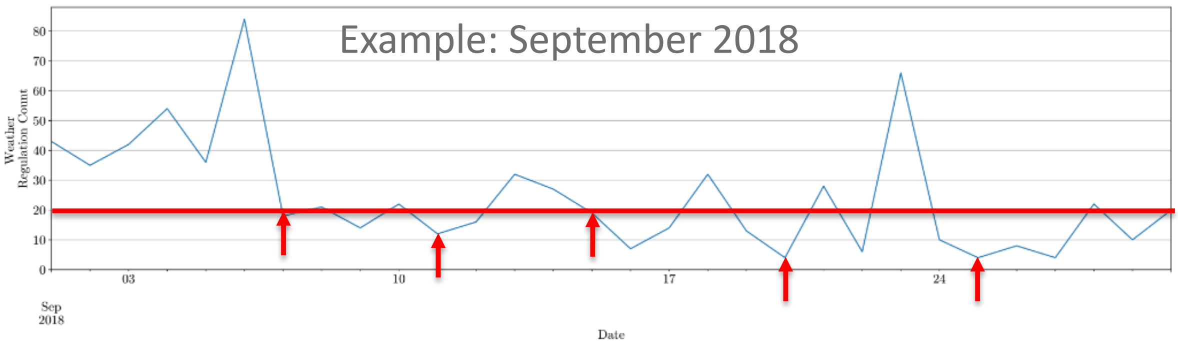

Figure 8: Demonstration of study day selection rule in September 2018 by way of example

This eventually led to the following 20 study days:

March:	5, 10, 15, 20, 25
June:	13, 15, 18, 23, 27
September:	7, 11, 15, 20, 25
December:	5, 10, 15, 20, 25

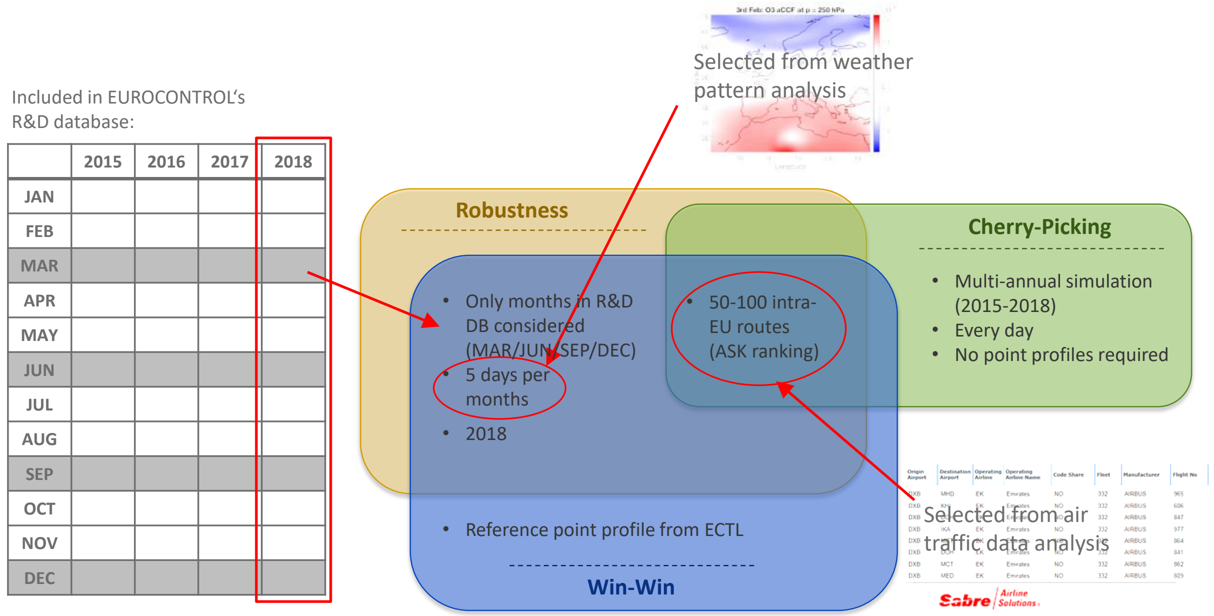

Figure 9: Case study specificities and sample data selection

B.6.2 Robust solutions

The robust solutions under uncertainty will be determined in two different ways:

Unconstrained ("free-flight") method:

The unconstrained method aims at identifying theoretical maximum mitigation potentials of climate-optimised flight planning. The focus is to draw conclusions valid for a large fraction of the European aviation and for a variety of weather situations. It is acceptable that routes are grouped by representative artificial routes as long as the error is proven to be small. This method leads to solutions, which cannot be flown today.

Graph-based method:

The graph-based method considers the real ATS route structure in the European airspace and therefore realistically captures the infrastructural requirements of today's flight planning processes. This method leads to solutions which are flyable today.

Both methods will analyse the traffic scene on the 20 selected study days. While the unconstrained approach will use the 100 most important artificial routes from the artificial route network, the graph-based method will start with the 100 most important (in terms of ASK) real routes. If computational effort permits, the process is extended to the next relevant flights in the list. The flight ranking has been prepared based on the analysis of flight schedule data from Sabre for winter and summer flight plan.

In the graph-based method, the aircraft type of the corresponding route is considered. In the unconstrained case, the aircraft type, which is dominating (in terms of ASK) the route cluster is used to simulate and optimise the flight. For all flights two departure times 00:00z and 12:00z are assumed. Although this is a simplification, the weather variability is considered through the different days. Moreover, it is made sure that both day-time and night-time contrail impact can be studied.

With the selected criteria from section B.6.1 the main parameters for the optimization runs are established. Due to the different optimisation approaches implemented in TOM and ROOST, the aforementioned fictitious route network will be simulated for the former, and the 100 most relevant routes in terms of ASK will be simulated for the latter. In both cases however, a similar approach is applied for the experiments and their execution:

1. After the initial setup of both tools, the implementation of EPS forecast consideration within the optimisation tools is validated. Routes previously analysed within the predecessor project ATM4E are considered applying the EPS forecast weather ensembles and results are compared to verify the implementation. Initial results may be used to verify early assumptions and expectations.
2. Once validated, each tool will be modified in order to enable batch processing capabilities of the selected route network (fictitious route network and top 100 routes by ask from 2018).
3. The main experiments will then be run once validation of tools and batch-processing are completed and setup. UC3M's ROOST has GPU-acceleration capabilities and is expected to run the experiments on a shorter timeframe than the optimal control-based TOM.

This procedure will be performed by scientists from both involved partners, UC3M and TUHH, in the experiments for their own tool respectively and on a similar timeline.

B.6.3 Win/win situation

The win/win situation case study is strongly related to the Robust solution case. Here, the objective is to compare the optimization potential that can be gained by an unconstrained optimization with the potential of the constrained optimization on the same route. By this, it will be shown that there are cases (=win/win situation), in which the aircraft operator can also benefit from climate-optimised flight planning in a monetary way.

In this case, only one study day is used. For 9 selected flights (route-aircraft combinations) both the constrained and the unconstrained solutions are computed and compared.

B.6.4 Eco-efficient solutions

The eco-efficient solutions case study takes place in a different setting. The study is carried out with the AirTraf submodule of the climate-chemistry model EMAC. Therefore, it is possible to perform an every-day simulation and even consider more than just one year. A one year simulation is done for the period of December 2017 to December 2018, and trajectories for the most important routes assuming just one aircraft type are optimised. For this study, no real point profiles are required, nor is ATS route information necessary.

B.6.5 Sequence of experiments

The experiments are carried out in the following sequence:

no.	title	actor	scenario			timing
			model	routes	weather	
#1	"Eco-efficient solutions" campaign	WP3 researcher, TUD (F. Castino)	EMAC/AirTraf	Top 100 real routes	One year, every day (1 Dec 17 to 1 Dec 18), two departure times (0000z and 1200z), no	Start: 6 months before D3.2 delivery; end: 4 months before D3.2 delivery

					ensembles (deterministic)	
#2	"Robust solutions" campaign – part 1 (constrained)	WP2 researcher, UC3M (A. Simorgh)	ROOST	Top 100 real routes (5 Pareto points)	5 days in Jun 2018, 5 days in Dec 2018, two departure times (0000z and 1200z), 10 ensembles (stochastic)	Start: 5 months before D2.2 delivery; end: 3 months before D2.2 delivery
#3	"Robust solutions" campaign – part 2 (unconstrained)	WP2 researchers, TUHH (B. Lührs, M. Meuser)	TOM	Top 10 fictitious routes (50 Pareto points)	5 days in Jun 2018, 5 days in Dec 2018, two departure times (0000z and 1200z), 10 ensembles (deterministic)	Start: 4 months before D2.2 delivery; end: 2 months before D2.2 delivery
#4	"Win/win situations" campaign	WP3 researchers, UC3M (A. Simorgh), TUHH (B. Lührs)	ROOST & TOM	9 selected real routes	One day (5 Dec 2018), one departure time (0000z), one ensemble (#1), no uncertainties	Start: 3 months before D3.2 delivery; end: 1 month before D3.2 delivery

B.7 Specific validation exercises

Some specific validation exercises were identified that support the sequential validation strategy described above. In the following four of them are named.

(1) Validation of the optimisation approach:

Logging performance parameters of individual trajectories calculated using the cost functions during optimisation will enable the validation of the optimisation approach.

By that, all relevant aircraft state properties can be monitored and analysed any time after the optimisation run. By that, it can be checked, whether the optimiser really points towards the best solution.

Validation criterion: The optimisation is valid, if it leads to the trajectory with the minimum cost function value.

Remarks: In the case of the optimization in a structured airspace, the graph-based approach (e.g. Dijkstra or A*) inherently guarantees to find a global minimum. A verification of a correct implementation of the algorithm therefore seems to be appropriate for the validation. In the case of the unconstrained optimization, three mechanisms are feasible: (1) an artificial high-resolution graph is constructed to compare the Optimal-control solution with the graph-based solution; this would help to judge whether the optimizer finds the global optimum or converges to a local optimum; (2) all interim solutions of the optimizer are stored in order to analyse afterwards, whether the trajectory with the minimum cost function value has been selected; (3) if in the "win/win situation" campaign the unconstrained optimizer finds better solutions than the constrained optimizer, the probability is high that the global optimum was found. It should also be noted, that by calculating 50 different points along the Pareto frontier with TOM, any irregularities (e.g. from converging into local minima) can be excluded.

(2) Validation of the route clustering algorithm:

By calculating the impact of both real routes and artificial routes within the generated traffic sample a validation of the route clustering algorithm will be possible.

The route clustering approach is used to reduce the complexity of the optimisation problem. It combines real routes connecting the same pairs of grid cells. While this approach might reduce the amount of processible routes to a large extent, errors are induced, which have to be analysed and considered acceptable.

Validation criterion: The simplification from the route clustering approach is acceptable, if the difference in the climate impact between the real route and the artificial route is below 5%.

Remarks: It is considered accurate enough, if the climate impact in this case is calculated in a simplified way by integrating the aCCFs along a great circle between departure and destination at a constant altitude. This will be done both for selected real routes and their corresponding artificial substitution routes.

(3) Risk assessment

The provision of R-aCCFs will enable to perform a risk analysis in order to quantify how large estimates might become in case that uncertainties are considered (e.g. weather forecast).

Validation criterion: The risk assessment is passed, if the spectrum of possible estimates considering uncertainties is quantified for a variety of cases.

Remarks: In this context, a risk may occur, if due to a high uncertainty in the weather forecast the optimizers compute flight plans that in contrast to the expectations actually lead to an increased climate impact. This can be analysed by performing hindcast studies and by evaluating the resulting flight plans under those meteorological conditions that actually occurred and that also can be obtained from ECMWF Reanalysis data.

(4) Validation of identification of "contrail days"

A comparison with satellite images (DLR has access) could support the validation of the identification of those days when fuel optimal solutions would intersect contrail forming regions.

This is important for the automatic detection of certain relevant weather situations.

Validation criterion: The identification mechanism is valid, if a high degree of correlation with satellite images can be observed.

Remarks: The automatic detection of contrails in satellite images is a complicated challenge itself and subject to ongoing research, with contributions from artificial intelligence. The correlation with satellite images should therefore be done "manually" by humans. In this case, experts should simply estimate the degree of correlation by looking at the images carefully. Three different experts are asked in parallel to obtain an objective result here.

B.8 Expected results

The description of the experimental set-up is widely provided in D2.1. Results of the experiments will be included in the respective deliverables and project reports, i.e. in D2.2 and D3.2. Furthermore, results will be published in scientific peer-reviewed journals.

In SESAR projects, the creation of Operational Improvement steps (OI steps) or Enabler (EN) is common practice. Currently, two solutions are proposed by FlyATM4E (see above).

Moreover, it is not planned to innovate new performance indicators. Instead, existing climate impact KPIs, such as e.g. Average Temperature Response (ATR), will be adopted.

The obtained results will be available in form of figures, tabulated data (e.g. CSV files) and in a structured easily readable form using the JSON format. Also, MATLAB format is provided as well as NETCDF files. After the experiments have been carried out, in a post-processing step data is aggregated and visualised, e.g. by appropriate maps and projections.

B.9 Data and software input

The relevant models used to carry out the experiments rely on certain data input. Main input data are weather data (ECMWF), flight plan data (Sabre ADI) and aircraft performance data (BADA). The respective licenses are available. Beyond these, no open data sources are used for the studies.

All data are processed based on experience from earlier projects and the necessary software and interfaces are available and have been adapted.

B.10 Research coordination

The data produced in FlyATM4E will be made available through publications upon request. For the reproduction of results by third parties (outside of the consortium), however, certain requirements have to be fulfilled. For instance, licenses to access and obtain the necessary input data (see above) are required. Moreover, the methodology has to be reproduced. This can partly be done with information from deliverables and publications. However, the original tools are proprietary and cannot be provided. Source code will not be published. Tool documentation and corresponding publications are widely available. The reproduction of results eventually also requires sufficient expertise in the research domains of FlyATM4E.