MULTI-AIRCRAFT ENVIRONMENTALLY-SCORED WEATHER-RESILIENT OPTIMISED 4D-TRAJECTORIES

Nick van den Dungen, Kinanthi Sutopo
Royal Netherlands Aerospace Centre (NLR)
Xavier Prats
Universitat Politècnica de Catalunya - Barcelona Tech (UPC)
Vittorio Di Vito
Centro Italiano Ricerche Aerospaziali (CIRA)
Angelo Riccio
Università degli Studi di Napoli Parthenope (UNIPARTH)

Abstract
Weather phenomena are one of the biggest causes for significant delays and unpredictable disruptions within air traffic management (ATM) network operations. The changing global climate increases the future severity and frequency of these air traffic disturbing weather phenomena. This deteriorates the predictability of 4D trajectory ATM network planning and potentially increases the delays within air traffic operations. Furthermore, aviation itself has a responsibility to mitigate its climate impact to improve the long-term sustainability of the ATM operations and to contribute to the global effort towards the reduction of anthropogenic climate change. The SESAR2020 exploratory research project CREATE (Grant 890898) aims to find answers on how to improve the weather-resilience of ATM-operations and to reduce its climate impact. A concept of operations (ConOps) has been developed which describes an integrated trajectory optimisation framework to tactically define environmentally-scored optimised 4D trajectories, for a multi-aircraft airspace configuration, using advanced numerical weather prediction models, combined with air traffic control (ATC) driven demand-capacity balancing methods. The framework will be applied to an en-route use-case focusing on the unorganised traffic over the North Atlantic, and a Terminal Manoevring Area (TMA) use-case focusing on the Naples Capodichino airspace. The optimised trajectories aim to evade thunderstorms and contrail formation regions, whilst minimising CO_2, non-CO_2 and local air quality (LAQ) impacts.

Keywords: ATM operations, environmental-impact, weather-resilience, 4D trajectory optimisation, climate-impact, numerical weather prediction.

Introduction
Weather phenomena such as low clouds, fog, rain, lighting and thunderstorms may affect the visibility around an airport or safe operability of aircraft which can cause delays or disruptions in flight schedules. The severity and frequency of these weather phenomena may increase due to the changing climate. As the Earth's surface temperature rises, convection activities increase which ultimately results in more extreme weather phenomena and increased concentrations of water vapor at higher altitudes. The intensification of the severity and frequency of hazardous weather phenomena has already been observed and reported in the most recent IPCC report (IPCC 2021). The frequency and intensity of heavy precipitation levels and hot extremes have increased since the 1950s and the IPCC report states that it is likely that anthropogenic climate change is the main driver. As global warming is unavoidable (the question remains to what extent humans can limit the temperature rise), it is highly likely that hazardous weather phenomena will continue to increase in severity and frequency.

CREATE research on weather impact on ATM and ATM impact on climate
To research the weather-resilience of air traffic and the anthropogenic climate impact, these relations have been analysed on a local/regional and global scale. On the local scale, the impact of aviation on the environment around Naples Capodichino airport was studied. The consortium partners have access to detailed weather and air traffic data for Naples Capodichino airport, and therefore this airport and its environment were selected as areas of interest for this study. To calculate the hourly and yearly averaged non-CO_2 concentrations on the local scale a Lagrangian particle code (SPRAY LPDM) was used and for the regional scale the FARM model was used. Specifically, the NO_x, PM_{10} and SO_2 emissions were calculated for the local scale due to the airport activities, and for the regional scale NO_x, non-methane volatile organic compounds (NMVOC) and $PM_{2.5}$ concentrations (CREATE, D2.1, 2021). Furthermore, a detailed description of microscale effects was attempted, considering the presence of buildings and obstacles around the Capodichino airport, using realistic weather data and flight paths (MicroSPRAY LPDM) (CREATE, D3.1, 2021). For the analysis on the global scale, it was recognized that calculating the radiative forcing (RF) effects from contrail formation is subject to uncertainties as current knowledge is insufficient to accurately predict and model (persistent) contrail formation. The RF effects of contrail formation however, are probably the largest of the aviation CO_2 and non-CO_2 climate impacts. (EASA, 2021) Thus, in order to reduce the aviation RF, the possibilities to avoid contrail formation by means of No-Fly Zones (NFZ) (with zero or reduced capacity) are explored within CREATE.

Furthermore, hazardous weather phenomena for ATM operations were identified. Lightning or thunderstorms can cause disruptions to flight schedules; aircraft are surprised by sudden wind changes or strong microbursts/downbursts induced by thunderstorms which can result in aircraft-stall, overstressed airframes and eventually structural failure and loss of control. Therefore, thunderstorms are extremely dangerous and must be avoided by aircraft. For Naples Capodichino airport thunderstorms were identified to be a major disruptive weather scenario. In 2019, over 1000 Dangerous Thunderstorm Alerts (DTA’s) were issued in Italy out of a total of 7372 throughout Europe.[1] Given the changing climate, the development of thunderstorms will become more irregular which makes it difficult to consider in the flight planning and execution stage. Therefore, CREATE explores options to integrate tactical accurate thunderstorm forecasting to have a more accurate prediction during the flight and optimise the flight plan whilst taking ATC sector constraints into account.

Objectives

One of the work packages within the CREATE project aims to find a potential solution suitable for the ATM operations to improve weather resilience and reduce its environmental impacts. It has been identified that convective areas related to thunderstorms are a severe disturbing phenomenon for ATM operations (CREATE, D2.2, 2021), and that from all non- CO_2 emissions contrail cirrus have a significant impact on the climate (EASA, 2021). This led to the generation of the CREATE trajectory optimisation framework, which aims to fulfil the following objectives; **1)** Reduce the weather-induced delay caused by severe weather phenomena, such as thunderstorms; **2a)** Minimise the environmental impact of candidate optimised trajectories, related to the evasion of contrail formation regions (CFR) for the en-route use-case; **2b)** Minimise the environmental impact of the candidate optimised trajectories, related to the LAQ for the TMA use-case. The CREATE research has two main contributions towards general ATM research; **a)** perform tactical trajectory replanning given an updated

[1] https://get.earthnetworks.com/resources/reports/2019-europe-lightning-report

weather forecast resulting from advanced numerical modelling, **b)** consider a "multi-aircraft" problem in which ATC restrictions and airspace capacity are considered as well.

Concept of Operations

The CREATE concept of operations (ConOps), related to the trajectory optimisation framework, addresses the integration of various design elements; **a)** multiple aircraft considered in the generation of 4D optimised trajectories; **b)** Numerical Weather Prediction (NWP) and Ensemble Weather Forecasting (EWF) is used for tactical trajectory replanning by predicting weather scenarios a few hours into the future of a given flight; **c)** implementing an environmental-score assessment for all proposed candidate routes in the system; **d)** Air traffic control (ATC) driven demand-capacity balancing (DCB) decision-making process to select overall optimum of the proposed trajectories within a use-case.

Figure 1 illustrates a scenario where multiple aircraft are considered in an arbitrary use case. In this scenario it is assumed that during the flight a set of thunderstorm zones propagates which were not considered in the initial flight planning stage. As such, once the considered aircraft are airborne and in the absence of any tactical trajectory optimisation framework, all aircraft eventually would need to be tactically manually guided by the air traffic controllers (ATCO), in coordination with the flight crew, around the thunderstorm zones to maintain safe flight operations. In air spaces with severe thunderstorm activity and high-density traffic, this becomes a tactical manual-intensive task for the ATC side with a high likelihood of severe weather-induced delays for the considered flights. Furthermore, the manual interventions disrupt the initially proposed flight plans, which has a potential snowballing effect on the delays of flights further downstream in the network.

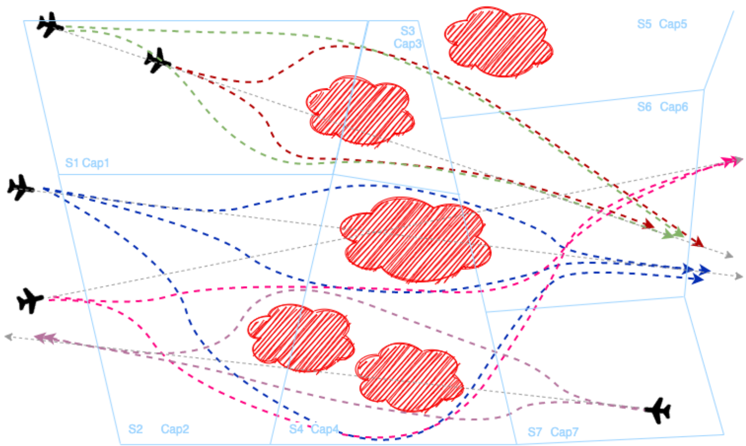

Figure 1: Illustrative example of the CREATE multi-aircraft candidate 4D optimised trajectories

The proposed CREATE ConOps aims to provide a solution to this problem by using NWP and EWF to uplink meteorological forecasts from the ground systems towards the considered airspace users (AU), which can use this data to accurately identify the no-go zones related to thunderstorms at a relatively early stage during the flight. When a thunderstorm front propagates along the flight plan, the AUs can propose candidate optimised 4D trajectories, to evade these areas. Various objective criteria's can be considered to proposes various candidate trajectories per considered aircraft, related to minimum fuel burn, or minimum delay, or minimum environmental impact. The trajectory optimisation framework can be expanded by integrating objective functions which aim to evade climate-sensitive regions related to contrail cirrus formation. Given the fact that contrail formation has a limited vertical domain

(Schumann 1996), the trajectory optimisation framework can consider flight level changes to efficiently evade these climate sensitive regions, without any lateral deviation.

Figure 2 illustrates how a centralized DCB component governed by ATC finally determines a global optimum from the set of proposed candidate trajectories by all AUs, to maintain balanced throughput across all airspace sectors considered in the system. This process includes as well an objective to select a solution with an overall minimum environmental impact, related to minimum CO_2 and NO_x emissions and/or minimum LAQ impact.

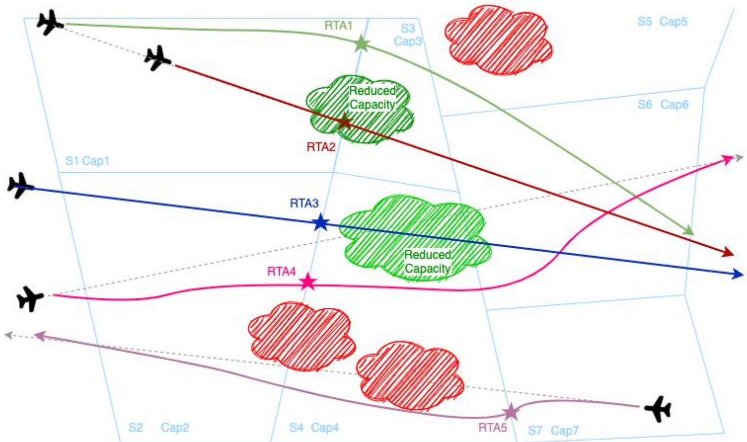

Figure 2: Illustration of the global optimum solution, related to the DCB element of the CREATE framework

Framework methodology

The framework which follows from the design elements consist of the following modules is visualised in Figure 3; **a)** Meteorological data provider (MDP). This is done via EWP; **b)** Thunderstorm and contrail-zone predictor (TCP). This is a set of algorithms which translates the EWP data into geographical areas and volumes to be evaded, i.e. the NFZ; **c)** flight plans (FP), these are the reference plans based on realistic reference flight; **d)** Sector definitions, these describe the geometric airspace sector layout horizontally and vertically; **e)** Trajectory Optimisation (TO) with aircraft filtering process (AFP), this module calculates various candidate optimised trajectory per aircraft. The AFP is used to filter per aircraft the relevant applicable data required for the optimisation process. The resulting output of the TO module is a set of new candidate flight plans, for all the aircraft considered in the optimisation problem; **f).** Trajectory Performance Reconstruction (TPR) with Trajectory Sector List (TSL) and Aircraft performance model (APM) based on BADA 4, this module converts all new flight plans into 4D trajectory profiles with detailed thrust and fuel-burn performances; **g)** Trajectory Emissions Calculator (TEC) with engine emission tables, this module calculates CO_2 and non-CO_2 related emissions such as NO_x and PM_{10} based on the output of the TPR module; **h)** Environmental scores method (ESM), this module calculates per candidate trajectory per flight an environmental impact score. For the en-route this will be related to the CO_2 and NO_x forming and for the TMA use-case this will be related to LAQ; **i)** Tactical Weather avoidance and demand and capacity balancing (TWADCB) based on available sectors capacity (SC); this module contains a set of algorithms which determines the global optimum of the computational scenario based on balancing the ATC load across all sectors, by selecting the best candidate flight plans out of all proposed options of the multiple considered aircraft; **j)** Decision making and pareto front analysis (DMPA), this module contains an ATC-based evaluation of the overall recommend solution scenario with the selected candidate routes. A human will be presented with the solution scenario and does a final sanity check on selected candidate trajectories.

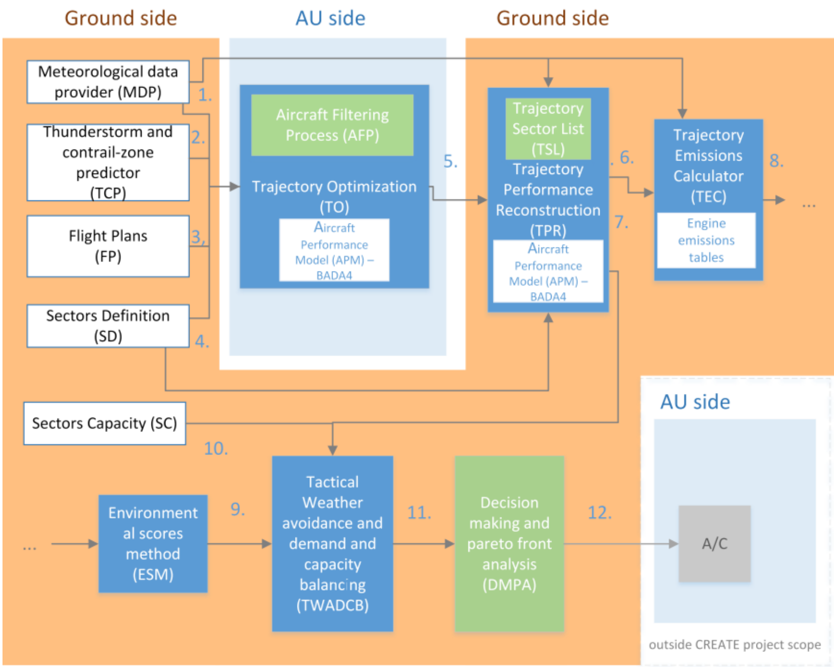

Figure 3: Overview of the CREATE framework related to the concept of operations

Ensemble weather forecast method

One of the key elements in the CREATE framework is the implementation of advanced weather modelling tools via NWP and EWF (ensemble NWP system). This allows flights to acquire accurate weather predictions during flight, which supports the tactical route optimisation process for long flights. The method used within the CREATE framework relies on taking the average EWF once a new weather ensemble is created every “x” min. The EWF members are used to calculate probabilistic NFZ within the TCP module, such that the weather prediction elements within the CREATE framework are not purely deterministic, but still include a probabilistic element. In previous SESAR research a method has been developed to provide the ATC DCB unit an optimised trajectory per EWF member. (IMET, 2015) However, since the CREATE framework considers multiple aircraft each providing multiple candidate trajectories, it has been decided to apply a simpler method to reduce the complexity at this exploratory phase of the research programme. This strategy supports the design philosophy to focus on providing an integrated framework to select a global optimum from the proposed candidate trajectories of the multiple aircraft considered in the use-cases.

Thunderstorm predictor via EWF

The TO module of the CREATE framework is triggered by the identification of thunderstorm related NFZ which require the original flight plan to be updated. Thunderstorms can be identified by the presence of high Convective Available Potential Energy (CAPE) values, which is derived from the ensemble NWP system. CAPE describes the amount of work that the upward buoyancy force would perform on a given air parcel if it travels upward through the atmosphere. (ECMWF, 2019) A positive CAPE indicates that the air parcel has the potential energy to rise and thus it indicates atmospheric instability. The higher the CAPE value, the more instable the atmosphere and the higher the possibility of thunderstorms and hail. A thunderstorm is defined if the most unstable CAPE (MU-CAPE) is larger than a critical threshold value for which severe thunderstorm form. The MU-CAPE method loses the vertical distribution of thunderstorms due to the integral along the vertical direction. As such, the TO module is limited to always evading thunderstorms laterally.

Contrail-zone predictor via EWF

The TO module of the CREATE framework is triggered as well by the identification of contrail cirrus related regions which require the original flight plan to be updated. Contrail-sensitive areas can be selected using the Schmidt-Appleman Criterion (SAC) (Schumann, 1996). Given the thermodynamic atmospheric conditions (temperature, air pressure and relative humidity) from the ensemble NWP system, and aircraft-specific parameters (fuel emission index, specific combustion heat and aircraft propulsive index), the SAC theory predicts conditions at which contrails can form, and whether these contrails will persist. According to the SAC, the temperature at which contrails form at the actual relative humidity is calculated for each vertical level. In this manner, the minimum and maximum height at which contrails are persistent is calculated for each model grid column. Therefore, the TO module could also use flight level changes to fly over or under a given contrail NFZ. Since the local atmosphere can be unstable, contrail formation conditions can change on the short term. It should therefore be noted that the contrail-zone predictor requires regular updates to account for the instability of the atmosphere.

Trajectory optimisation criteria and objective functions

The following considerations are used to provide the candidate optimised trajectories: **a)** the alternative trajectories will avoid the conflicting NFZ (one or more); **b)** the alternative trajectories will minimize the deviation from the original path; **c)** the alternative trajectories will be calculated in the 2D framework and after that the vertical profile will be associated to them; **d)** the alternative trajectories will have minimum curvature radius in the 2D framework that will comply with the nominal performances of the considered aircraft; **e)** the alternative trajectories will have vertical flight path angle envelope that will comply with the nominal performances of the considered aircraft.

Environmental scores method for en-route

The ESM for en-route takes both CO_2 and non-CO_2 effects into account. Most important to identify is that the climate impact of CO_2 is directly related to emission amount and independent of time and place of emission, whereas the climate effect of non-CO_2 emissions is highly dependent on time and location of emission, due to the complex interaction with background concentration and influence of atmospheric and engine characteristics. The impact of contrails can be linked to the likelihood of flying through contrail formation zones, and the impact of NO_x emissions is dependent on NO_x background concentrations and engine characteristics. A trajectory with reduced CO_2 emissions can result in increased non-CO_2 climate impacts, e.g. because it will likely fly through CFR's or because lower CO_2 emissions are due to increased engine efficiency which leads to increased NO_x emissions. Furthermore, the time horizon of the impacts of CO_2 and non-CO_2 impacts vary, which is taken into account as well. The ESM for en-route takes all these variables into account and weighs these impacts into a final environmental score.

Environmental scores method for TMA

The ESM for the TMA starts with dividing each aircraft trajectory into segments, each one with the related portion of the emissions. The fate of those emissions in the atmosphere is then followed along multiple Lagrangian "environmental trajectories", calculated on the basis of current 3D meteorology and turbulence fields. The spread of each trajectory set gives an indication of the diffusion potential of the atmosphere at that time and location, and the environmental score of the aircraft trajectory is calculated as the sum of the spreads associated to all segments. This then can be related to local air quality.

Candidate routes selection via DCB
Within the TWADCM module an algorithm will perform the selection of the most suitable candidate flight plan for each and every aircraft by considering a weighted mean of the associated scores to each candidate trajectory based on both the environmental score associated to the trajectory and the sector capacity resulting from the associated path execution. For each alternative trajectory selected for the aircrafts of interest, the TWACB module also calculates the associated expected delay with respect to the nominal one.

Discussion on framework operational application
In the first phase of the project it has been established that the CREATE framework should be developed and applied to two different use cases, i.e. en-route and TMA. The weather, climate, and ATC specific phenomena have different characteristics per use case, yet equally important. Since the CREATE framework can be developed in a generic manner to be applied to both use cases, it is investigated what the framework specificities and potential benefits are per use-case.

En-route
For the en-route use case an area of interest needs to be defined which is sufficiently interesting to research based on the presence of CRFs and thunderstorm fronts. For European flights, the trans-Atlantic long-haul flights is an interesting use-case to consider. Since thunderstorms are likely to propagate over central mainland US[2] and Mediterranean Europe[3], it is likely that these phenomena affect the initial and last parts of the en-route flight segment. As researched by Irvine et al. (2012), the North Atlantic Ocean shows strong contrail formation. Therefore, it is likely that the middle part of the en-route flight segment for a trans-Atlantic flight is affected by contrail formation. Another reason why the North Atlantic routes are interesting to research is that different segments of the flight will be triggered by either thunderstorm propagation or contrail formation, due to the atmospheric conditions in which both phenomena persist. In terms of the ESM, the Lagrangian method related to LAQ cannot be applied because it considers assumptions which are only valid for low altitudes and is mainly relevant for populated areas.

TMA
Within CREATE Italy will be considered as a particular country of interest, given its many thunderstorm activities throughout the year. Furthermore, the availability of detailed local meteorological and environmental information for Naples Capodichino airport led to the selection of the Naples TMA as use-case for the TMA operations. The CREATE research shall investigate how the TMA operations, including continuous descent operations (CDO), will be affected due to the application of the CREATE framework. Given the meteorological conditions which are required for contrail cirrus to propagate, i.e. cold/stable/moist atmospheres, it is unlikely that contrail cirrus will affect the TMA use-case.

Conclusion
The work presented shows the CREATE ConOps, which is a framework considering multi-aircraft environmentally-scored weather-resilient optimised 4D trajectories, aiming to evade thunderstorm areas and contrail forming regions, with the objective make the ATM operations more weather-resilient whilst minimising its environmental impact. By using EWF various candidate optimised trajectories can be developed where a centralised ATC-based DCB decision-making process will select the global optimum for a given use-case scenario.

---

[2] https://www.spc.noaa.gov/wcm/
[3] https://www.essl.org/cms/a-climatology-of-thunderstorms-across-europe/

The next step in the CREATE research is to demonstrate the effectiveness of the framework on the en-route and TMA use-cases, which are the North Atlantic and Naples TMA respectively. Per use-case, validation simulations will be performed to derive conclusions whether the CREATE framework can effectively reduce the ATM delays and environmental impact, compared to applicable reference scenario(s).

Acknowledgements
This project has received funding within the framework of the SESAR Joint Undertaking project "Innovative Operations and Climate and Weather Models to Improve ATM Resilience and Reduce Impacts" (SESARH2020-ER4 CREATE) within the European Union's Horizon 2020 research and innovation programme under grant agreement No 890898. The CREATE consortium is formed by ATM/Meteo/Environmental specialists from the Royal Netherlands Aerospace Centre (NLR), Universitat Politècnica de Catalunya (UPC), Centro Italiano Ricerche Aerospaziali (CIRA), Università degli Studi di Napoli Parthenope (UNIPARTH, project coordinator), ARIANET, Ilmatieteen Laitos (Finnish Meteorological Institute, FMI), and Institute for Sustainable Society and Innovation (ISSNOVA).

References

EASA (2021), *Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4).* Brussels, European Commission.

ECMWF (2019), *An overview of Convective Available Potential Energy and Convective Inhibition provided by NWP models for operational forecasting.* Reading, European Centre for Medium-Range Weather Forecasts (ECMWF).

E. Irvine, B. Hoshkins, K. Shine (2012), *The dependence of contrail formation on the weather pattern and altitude in the North Atlantic*. *Geophysical Research Letters,* Vol. 39, No. 12.

IPCC (2021), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Schumann, U. (1996), On conditions for contrail formation from aircraft exhausts. *Meteorologische Zeitschrift*, Vol 5, No 1, 4–23.

SESAR-ER4-CREATE (2021), *D2.1: Aviation impact on local environment and long term & global phenomena – ed00.02.00.* Brussels, SESAR Joint Undertaking (SJU).

SESAR-ER4-CREATE (2021), *D2.2: Analysis of vulnerability of ATM to weather phenomena – ed00.02.00.* Brussels, SESAR Joint Undertaking (SJU).

SESAR-ER4-CREATE (2021), *D3.1: Local and regional models integrated with weather and climate information – ed00.01.00.* Brussels, SESAR Joint Undertaking (SJU).

SESAR IMET (2015), *Technical Final Report of the IMET project WP-E.02.40.* Brussels, SESAR Joint Undertaking (SJU).