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CO_2 and non-CO_2 balanced Environmental Scores Module for flight performance evaluation and optimisation

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Abstract. The SESAR2020 exploratory research (ER4) programme CREATE (Grant 890898) developed a climate and weather aware Concept of Operations (ConOps) which encompasses a multi-aircraft 4D trajectory optimisation framework, which utilises a CO_2 and non-CO_2 balanced Environmental Scores Module (ESM) for the en-route flight phase. The ESM provides a computational method to evaluate the "greenness" of aircraft trajectories. Some components related to the internal ESM scoring are based on expert judgement, which is in line with the technology readiness level (TRL) 1 of the solution. Fast-time simulations were performed to demonstrate the proof-of-concept of the ESM in a multi-aircraft tactical optimisation scenario in the North-Atlantic region. The results show that, because of the simplicity of the metric, the ESM could be well used for trajectory optimisation and tactical replanning, and most likely as well as flight and ATC sector environmental performance evaluations.

1. Introduction

Aviation has a responsibility to mitigate its climate impact to improve the long-term sustainability of its operations and to contribute to the global effort towards reduction of human impact on climate changes. Although much research is ongoing towards the understanding of CO_2 and non-CO_2 impacts of aviation, key stakeholders such as airlines, service providers, and regulators are struggling to translate this knowledge into pragmatic metrics which can be used to incentivise reduced climate-impact flight operations.

In the context of CREATE, a SESAR 2020 exploratory research project, a potential SESAR solution was proposed aiming at the revision and update process of the reference business trajectory in the particular case of scenarios disrupted by severe weather conditions, and taking into account the environmental impact of the operations (CREATE-SOL-2). In this context, an air traffic control (ATC) decision support tool (DST) was proposed in line with the SESAR extended ATC planning (EAP) and integrated network for (extended) ATC planning (INAP) concepts. The basic idea behind CREATE-SOL-2 is that, during the execution of a flight, several alternative trajectories might be proposed by the airspace user in order to avoid weather hazards or climate sensitive volumes using the most up-to-date weather and environmental impact information available. Then, for each alternative trajectory, an *environmental score* is computed and used by the DST to inform ATC and to support the selection of the best avoidance trajectory for each concerned flight to find a system-wide optimum [1].

Hence, the Environmental Scores Module (ESM) was proposed and identified as a candidate SESAR solution by itself (CREATE-SOL-3), since it might be embedded in other air traffic management (ATM) systems and/or be used with other trajectory look-ahead times (such as for instance for flight dispatching or air traffic flow management purposes). The ESM specifically addresses the CO_2 and non-CO_2 effects during the en-route flight phase. The solution is used to evaluate the "green" performance of aircraft trajectories related to flight and ATC sector environmental performance which is useful in performance dashboards for airlines and ATC service providers. In the CREATE fast-time simulation experiment the ESM was used within the trajectory optimisation framework to rank the candidate flight trajectories which are then used by a trajectory selector module to select the overall solution, depending on the user-based decisions between operational cost and delays vs environmental performance in the decision support tool module.

The ESM is the core of this solution and it assigns scores to each candidate trajectory. It considers non-CO_2 emissions, which are dependent of location and time, and CO_2 emissions, which are independent of location and time. Therefore, CO_2 and non-CO_2 emissions are treated differently in the ESM. This paper focuses in the ESM and explains the methodology followed and rationale behind to build these environmental scores. Some illustrative examples are also given corresponding to fast-time simulations of flights crossing the North-Atlantic, which were used to demonstrate the proof-of-concept of the ESM.

2. The CREATE SOL-2 framework

Figure 1 shows the different modules that compose the CREATE SOL-2 concept, along with their high-level interactions. The **Meteorological data provider (MDP)** and the **Thunderstorm and contrail-zone predictor (TCP)** are external providers to the proposed Decision Support system. The **active reference business trajectories (aRBTs)** (i.e., the last update of the RBT for each flight), which basically represents the traffic demand, the **sector definition (SD)** and the **sector capacities (SC)** are available on ground and transferred to the airspace users (AUs) if required.

After these first modules, which aim at providing the initial input data, the next module is the **Aircraft Filtering Process (ADP),** in charge of filtering the flights of the indicated area of interest (AoI) and also the flights which cross any thunderstorm or contrail area. All flights included in the AoI will be considered, but the alternative trajectories will be requested only for the flights crossing some weather conflicting area.

The **Trajectory Optimisation (TO)** module aims at simulating the AUs behaviour when they have to provide alternative trajectories. The main goal of this module is to provide the alternative trajectories that avoid the thunderstorm and contrails while minimising the impact to the airspace users. Within CREATE, these alternative trajectories are modelled considering BADA4 and BADA 3.9 for the **Aircraft Performance Model (APM)**. The output of this module is the set of all alternative trajectories of all flights crossing the area of interest. These trajectories are supposed to be sent to the ground-based ATC DST in from of extended flight plan, i.e., list of waypoints with an associated time of arrival.

Once all trajectories (in from of flight plan) are available, they are shared with the **Trajectory performance reconstruction (TPR)**. The purposes of this TPR are to reconstruct the full trajectory from the flight plan, the creation of the **trajectory sector list (TSL)** that each trajectory is crossing and to estimate the required performance data in order to be able to estimate the emissions of the indicated trajectories (initial and alternative) in a later module. This module is called **Trajectory Emissions Calculator (TEC)**, which uses the available data of the engines for the estimation of the emissions. Then, the **Environmental Scores Method (ESM)** module translates those emissions into environmental scores which allows us to consider the environmental impact of all trajectories.

Once all the initial/alternative trajectories are available together with their environmental score, their sector crossing list and the sector capacities are given, the **Trajectory Selector (TS)** is deployed. This module aims at choosing one trajectory for each flight at the same time it ensures that the demand is below the capacity for all the available sectors and contrail zones in the area of interest. Note that the contrail zone is considered as an artificial sector with a given capacity in order to limit the amount of flight in the region.

Finally, there is the **Decision Making and Pareto Analysis (DMPA)**. It is possible to run the TS many times considering different objectives and then evaluate the cross impact between different KPA/KPIs. Thus, a Pareto analysis can be conducted in order to take conclusions and make decisions. The final trajectories, along with the allocated delays, are supposed to be communicated to the AUs.

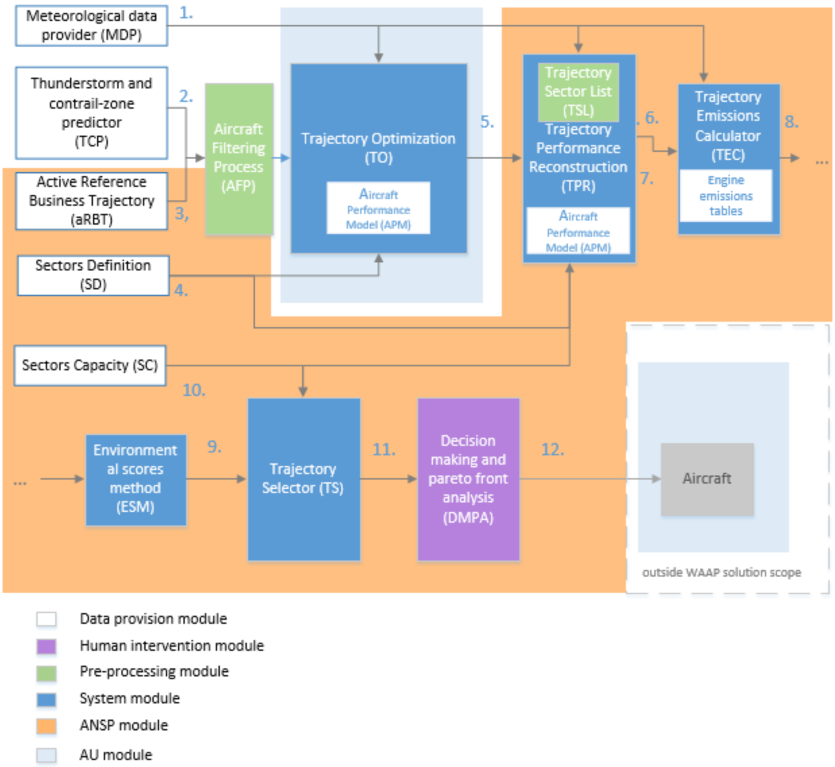


Figure 1: CREATE-SOL-2 framework, principal modules and their interactions. The ESM (CREATE-SOL-3) is embedded in the CREATE-SOL-2 framework.

3. Methodology to compute the ESM

The ESM for the en-route use-case relies on scoring the candidate trajectories (CT) from the TO module, based on the expected CO_2, non-CO_2 emissions and contrail formation potential.

3.1. Concept

The CO_2 and NO_x emissions along the (full) flight trajectory of each CT are determined using local atmospheric properties, aircraft speed and fuel flow. Weather predictions are used to identify temporarily contrail sensitive areas. For those parts of the flight trajectory that overlap with contrail/climate sensitive areas, the likelihood of contrail formation is assessed. Trailing behind the aircraft engine exhaust is a plume with a cross section that increases by distance to the aircraft. Inside the plume, the water vapor emissions are diluted, while the temperature decreases due to mixing with the outer atmosphere. Because flight corridors might be fairly busy, it is also checked whether local relative humidity (at the aircraft position) is increased by the plumes of aircraft flying nearby. If this happens, the preceding aircraft engine emissions concentrations are added to the local atmospheric conditions.

The prediction of persistence of contrails is based on the Schmidt–Appleman criterion, adapted by Schumann [4], which translates the engine partial conversion of combustion heat into kinetic energy and resulting higher temperatures in the aircraft plume. The formation of contrails is then predicted by the dilution process in the plume and the local atmospheric conditions, including relative humidity, local temperature, freezing and dew point temperatures. This criterion predicts whether a contrail will form and, if formed, will be persistent or short-lived. Subsequently, the candidate trajectories are scored and this information is forwarded to the next modules. This is schematically depicted in Figure 2.

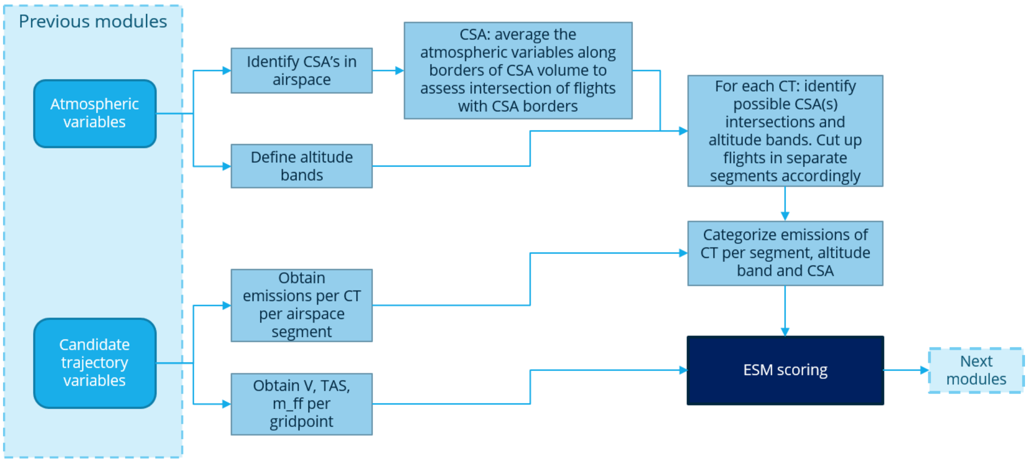


Figure 2: CREATE-SOL-3 ESM concept schematic

In the Decision Making and Pareto Frond Analysis (DMPA) module of CREATE-SOL-2 the ESM score is used as input for the decision making to select the most optimal trajectory, taking into account environmental and capacity conditions and constraints.

3.2. Scoring rationale

In terms of non-CO_2 emissions, the ESM considers NO_x, H_2O and contrail formation. Figure 3 illustrates how the ESM score is built-up. The following considerations apply:

- **CO_2**: Since CO_2 climate impact is not depending on location or altitude, the performance of a CT in terms of CO_2 emissions is scored based on total emitted CO_2 and compared to other CTs;
- **NO_x and H_2O**: The climate impact of NO_x and H_2O emissions depends on the location, geographically and with respect to altitude, and time of emission, and the background concentrations present. This however, is subject to many uncertainties. It is known that the impact of these emissions increases with emission altitude [2][3]. Therefore, the impact of these emissions is related to emission altitude which can be easily obtained from the trajectory data. Emissions are assessed per flight segment and heavier weights are assigned to emissions at higher altitudes than average cruise altitudes, and lower weights are assigned to emissions at lower altitudes. For this assessment altitude bands, expressed in terms of atmospheric pressure, have been defined and weights are assigned to each altitude band, see Table 1. The weights are used to multiply the emissions per altitude band, which is then further used in the EMS score build-up (see Figure 3). At the current stage of the research, i.e. TRL1, it was decided to assign the weights per altitude/pressure band based on expert judgement. For higher TRL research it should be researched if this approach is sufficient for an aircraft trajectory environmental scoring metric.

Table 1: Altitude pressure bands and weights for NO_x and H_2O emissions

Pressure band base value	Pressure band top value	Weights for the emissions per pressure band
101325	90000	0.5
90000	80000	0.5
80000	70000	0.5
70000	60000	0.5
60000	50000	0.5

50000	40000	0.5
40000	30000	0.5
30000	25000	0.8
25000	20000	1.5
20000	0	2.5

The current scope considers Contrail Formation Region (CFR) to be relevant for the definition of CSAs, however the solution is sufficiently generic to include other meteorological phenomena as well in future developments of the ESM for use in the ATM solution selection and optimization. The ESM score is designed in such a way that the contrail formation likelihood is key to the score.

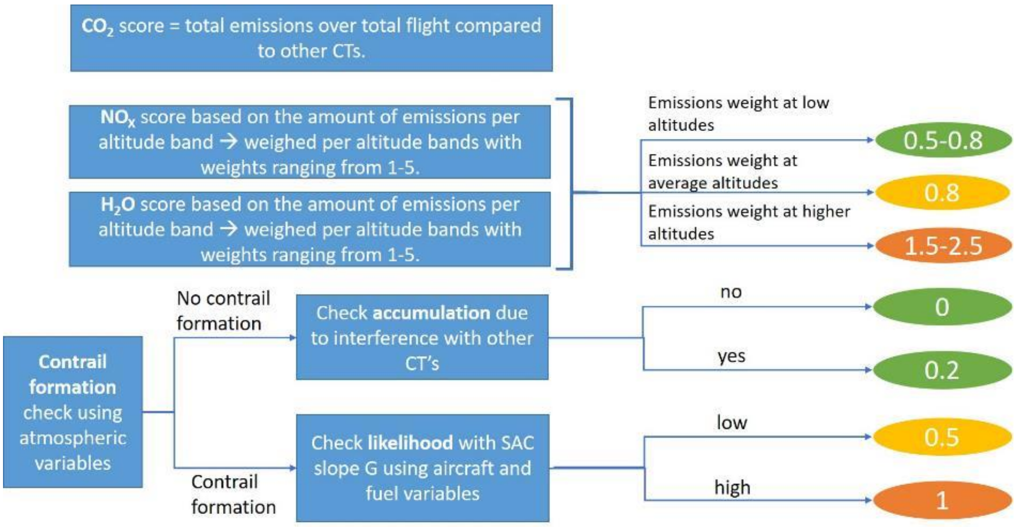


Figure 3: CREATE-SOL-3 ESM score build-up

3.3. ESM equation

The ESM scoring algorithm combines the CO_2, NOx, water vapor and contrail formation scores into a single environmental ESM score. Note that NOx emissions are relatively small to CO_2 and H2O emissions and in turn much larger than the contrail score that is expressed in a range from 0 to 1. For the purpose of comparison of alternative candidate trajectories for a single flight, the scores are normalized to the reference flight, candidate 0 (c0). The impact of CO_2, NOx and water vapor could be assessed using climate specific metrics like Average Temperature Response (ATR) for different time horizons, such metrics are computationally intensive and therefore not yet applicable for (tactical) ATM flight planning. For the purpose of this study, a simple equal weighting is assumed for the CO_2, NOx and water vapor. The ESM is designed to emphasize contrail formation in climate sensitive areas and dominates the score if the likelihood is larger than 50%. The overall ESM score is then defined by Equation (1).

$$ESM = \frac{\left(\frac{CO_{2\,score}}{CO_{2\,score,c0}} + \frac{NO_{x\,score,}}{NO_{x\,score,c0}} + \frac{H_2O_{score}}{H_2O_{score,c0}}\right)}{3} + 2 * Contrail\_score \tag{1}$$

Note the contrail score is in many cases not a property of a single flight candidate; the formation of contrail likelihood instead depends on the vicinity of neighbouring candidate trajectory by other flights. An ESM score is then always depending on one or more related candidate flights.

4. Fast-Time Simulation Exercise

An illustrative example focusing on the North Atlantic air space extending into the European Civil Aviation Conference (ECAC) area is shown in this section. The geographical domain and corresponding weather and traffic sample was based on the historical data of **27-07-2018**. For this specific day, Europe experienced a high weather-induced delays, as shown in the EUROCONTROL DDR2 data, with considerable thunderstorms and contrail areas present over the North Atlantic area. Figure 4 provides an overview of the computational domain including the Climate Sensitive Areas (CSA), related to contrail formation; and No Fly Zones (NFZ), related to thunderstorm formation). The following considerations should be taken for this use-case: contrail formation near Greenland; thunderstorm occurrences near central US and EU; and altitudes: FL285-FL420 (28,500ft to 42,000ft).

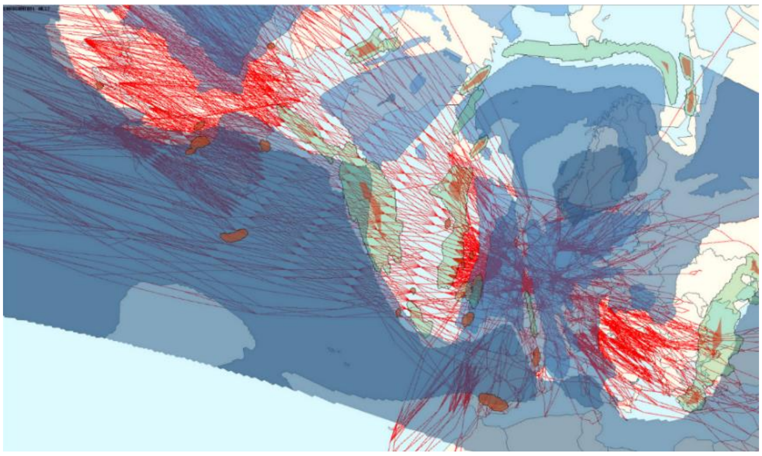


Figure 4: En-route use-case overview from the NEST tool, mapped on the North Atlantic region and Central Europe, based on 27-07-2018 historical data. Blue areas are CSAs, green areas are clear air turbulence, red areas are thunderstorm NFZs. The flight patterns are derived from EUROCONTROL DDR2 flight plan database. The CSAs and NFZs were acquired from the TCP module of the CREATE-SOL-2 framework.

In order to address the trade-off between environmental impact and cost for the AUs, two objective functions are considered in this illustrative example: the environmental contribution of the flights (C_k^E); and extra cost for the AU (C_k^{AU}), accounting for the extra fuel cost and delay induced by the avoidance trajectory if compared with the nominal flight plan. Then a compound objective function J is built by simply weighting these two objectives.

$$J = \sum_{k \in K} \left[\alpha C_k^E + (1-\alpha) C_k^{AU}\right] \tag{2}$$

where α is the weighting parameter (ranging from 0 to 1 and k is a trajectory within the set of trajectories K for a specific flight. C_k^E and C_k^{AU}, in turn, are defined as follows:

$$C_k^E = w_e \cdot E_k \cdot z_k,\ \forall k \in K \tag{3}$$

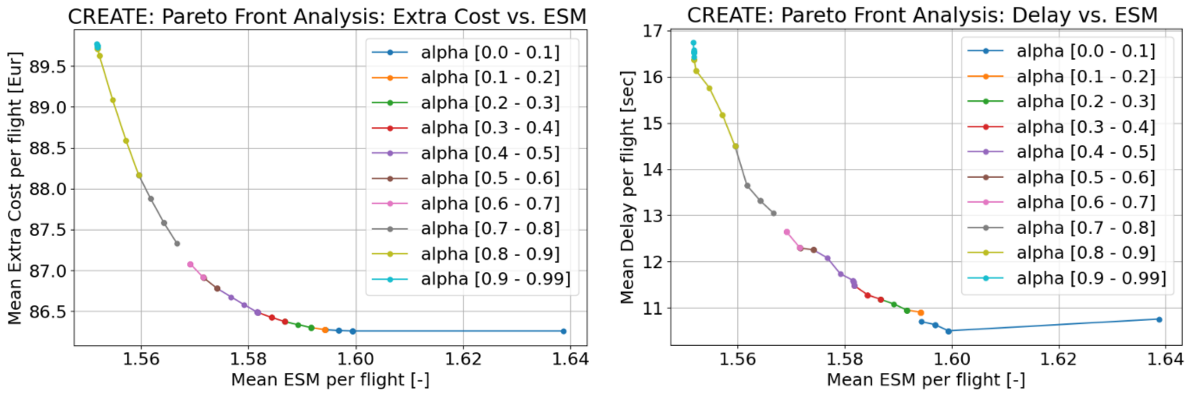
$$C_k^{AU} = w_c \cdot C_k^F \cdot z_k + w_d \cdot D_k,\ \forall k \in K \tag{4}$$

where w_e, w_c and w_d are the weighted costs of the ESM, displacement cost and delay, respectively. Currently, these weighted values are used to normalise the input data, so the sum is fair in terms of units. D_k is the delay allocated to candidate trajectory k when it crosses the first encountered sector.

5. Results

The output of the simulations results in a Pareto front, which is shown in Figure 5. For different relative weights between (α values), the mean ESM per flight is plotted versus the mean extra cost per flight (Figure 5a). The latter is related to the airline operating cost, which involves both fuel consumption and extra flight time/delay elements. The decision variable α is used to select a solution on the Pareto front.

- Higher α:
  - Lower ESM score, leading to “greener” flight solutions.
  - Higher extra operating cost per flight.
- Lower α:
  - Lower extra operating cost, leading to cost-effective solutions.
  - Higher ESM score, leading to higher-environmental-impact solutions.



a) Extra cost for the Airspace Users vs. ESM b) Delay vs. ESM

Figure 5: Pareto front analysis for the North-Atlantic case study (27-07-2018). The results show only one iteration of the tactical trajectory replanning (30min of flight).

The decision can also be based on the mean delay assigned per flight. **Figure 5**Figure 5b represents the whole network delay vs. the network environmental score. As aforementioned, for higher α values, “greener” flights solutions are obtained, which will generally lead to trajectories avoiding contrail areas. These “greener” solutions will stretch the flight trajectory paths, generally resulting in a higher global delay. In the “greenest” case, a global delay of 17 seconds is obtained. On the other hand, while exploring lower alphas (close to 0.0), the delay drops to 11 seconds.

Bear in mind that in this scenario no-go areas were included, forcing some “candidate zero” flights to be unfeasible. For these initial flights crossing, for instance, thunderstorms, the only solution was to divert laterally. Thus, leading to an offset into the global network delay and the total extra cost.

It should also be noted that the results shown above correspond to only one iteration of the tactical trajectory replanning algorithm, corresponding to 30 minutes of flight for this particular example. The CREATE-SOL-2 concept involves consecutive iterations of the algorithm to continuously adapt the trajectories every time a new weather update is received. Hence, the values of ESM and extra cost or delay shown above are those that are incurred in those 30 minutes of flight of this first iteration of the avoidance trajectory (hence the relatively low values).

6. Discussion and Recommendations

The objective of the CREATE-SOL-3 (ESM) was to develop a pragmatic metric which could be easily used in tactical trajectory optimisation. The ESM relied on scoring various candidate trajectories to select the most suitable option in the trajectory selection process of the ATC DST. The scoring weights and scoring equation however are still open for debate with a wider range of stakeholders to ensure that a “fair” evaluation is done of the CO_2 and non-CO_2 effects. Currently, the ESM scoring was done based on internal expert judgement which is in line with the TRL1 maturity of the solution. Yet, it would be recommended for future research to involve as well e.g., Air Navigation Service Providers (ANSP), airlines, and regulators to discuss the applicability and scoring of the ESM on a higher practical level.

In the en-route case experiment, many alternative trajectories per flight were generated. The number of candidate trajectories escalated quickly with the number of areas crossed by the baseline trajectories, due to the fact that there were many strategies that could be chosen to avoid these areas (e.g., divert to the left or right, avoid vertically, etc). The more areas to be avoided, the higher the possible combinations to avoid these areas, and the more alternative trajectories generated.
Having a higher number of trajectories led to higher computational times for the ESM module; that is one of the reasons why the number of alternative trajectories was limited to 11 in the en-route experiment. Furthermore, many trajectories were not operationally feasible, and many of them were filtered out. However, both the limitation in the number of trajectories and the filtering were done in quite a manual way. In the future, a more "intelligent" system would be needed to limit this number of trajectories. Moreover, assuming the computational times for the ESM will be lower, more trajectories could be generated for each flight, potentially leading to better results.

7. Conclusions

The solution presented in this paper is able to provide an initial quantification of the "greenness" of aircraft trajectories, combining both the CO_2 and non-CO_2 effects into a single metric. Because of the simplicity of the metric (the ESM outputs a single value per trajectory), it can be well used for trajectory optimisation and tactical replanning, as well as flight and ATC sector environmental performance evaluations (e.g., in performance dashboards for airlines and air navigation service providers). The implementation could be universally applied to flight trajectories, given the required meteorological information is present to perform the calculations. The current implementation is specifically addressing contrail formation, however future research could expand on other non-CO_2 phenomena. The current implementation should be further optimised for computational speed in a next research phase.

Within the scope of CREATE it was not decided for which ESM a trajectory is "green", however it did provide insights in how an ESM or similar environmental impact metric could be used the ranking of candidate trajectories in the ATM focused decision-making process. In general, it could be stated that based on the current mechanism of the CREATE-SOL-3 a greener trajectory has a lower ESM compared to a reference flight. The Pareto front analysis shows that trade-offs should be made between green flights and operating cost. As such, it could be used in practice that a given ESM threshold exists which decreases the selection space for the most cost-effective solution in the DMPA module.

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