Climate assessment of innovative mitigation strategies towards operational improvements in aviation

D1.5– Second iteration for the identification, assessment and selection of operational improvements

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CLIMOP Consortium

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Executive summary

This deliverable presents the list of individual OIs and the integration strategies which are planned to be investigated in the second round of assessment. Overall progress status of OIs in the first assessment round is also included to deliver an overview of the studies done in work package two up until the end of D2.3. The progress status is presented in terms of score points to show the actual status for each OI. A list of computed and remaining KPIs to be computed is also available for a more detailed perspective on individual OIs. Each OI plan for the second round, including its modifications and assessment process, is described in the third chapter. The plans described in the third chapter are roadmaps for the analyses in D2.4. Finally, chapter 4 illustrated integration strategies for three categories of OIs, namely network-related, trajectory-related, and groud operation-related scenarios. By integration strategies, we aim to use the synergy among OIs and generate a more realistic result. The integrations come with their requirements and challenges, which are discussed in all the involved working groups and presented in chapter four accordingly.

Abbreviations

#	number of
3D	three dimensional
AC	aircraft
ACACIA	Advancing the Science for Aviation and Climate
aCCF	algorithmic climate change function
AEDT	Aviation Environmental Design Tool
ALTERNATE	Assessment on alternative aviation fuels development
AJF	Al-Jawf Domestic Airport
ANSP	air navigation service providers
AOMAS	multi-agent airline operation planning model
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASK	available seat kilometres
ATAG	Air Transport Action Group
ATC	air traffic control
ATCo	air traffic controller
ATM	air traffic management
ATR	Average Temperature Response
ATS	air traffic service
BADA	base of aircraft data
BC	black carbon
BES	building energy simulation
BOS	Boston (Massachusetts) Airport
BXR	Bam Airport
CAS	calibrated air speed
CASK	cost per available seat kilometre
CCF	climate change functions
CFL	cruise flight level
CLIM	Climate-optimised flight planning
CMIP 5	Coupled-Model Intercomparison Project 5
CND	Mihail Kogalniceanu International Airport
CO	carbon monoxide
CO2	carbon dioxide
CYL	Coyoles Airport
CYU	Cuyo Airport
DBL	Deep Blue
DDR2	Demand data repository 2

DLR	German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt)
DOH	Doha Airport
DP	dynamic programming
DUB	Dublin Airport
DWD	German Weather Service (Deutscher Wetterdienst)
ECAC	European Civil Aviation Conference
ECMWF	European Centre for Medium-Range Forecast
EDUU	Karlsruhe upper area control centre
EE	Electrical energy
ECHAM	ECMWF Hamburg
EI	emission index
ELEC	electrification of ground equipment of an Airport
EMAC	ECHAM5/MESSy Atmospheric Chemistry Climate Model
EPS	expanded polystyrene
EU	European Union
FESG	Forecast and Economic Analysis Support Group
FL	flight level
FREE	free routing
FSP	St Pierre Airport
ft	feet
GFS	Global Forecast System
GHG	greenhouse gas
GRIDLAB	Global air traffic emission distribution laboratory
GreAT	Greener Air-Traffic Operations
HAM	Hamburg Airport
H2O	water vapour
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILS	instrument landing system
INEA	Innovation and Networks Executive Agency
INFR	Upgrade of the Airport infrastructure according to energy efficient criteria
IPCC	Intergovernmental Panel on Climate Change
ISO	intermediate stop operations
ISOC	climate-optimised intermediate stop operations
ITU	Istanbul Technical University
JFK	New York Airport John F. Kennedy
JNN	Nanortalik Airport

KLM	Royal Dutch Airlines (Koninklijke Luchtvaart Maatschappij)
KPI	key performance indicator
LED	light-emitting diode
LIN	Milano Linate Airport
LOSL	Flying low and slow
LTO	Landing and Take-off
MAD	Madrid Airport
MXP	Milano Malpensa Airport
NAFC	North-Atlantic flight corridor
NETW	strategic network planning
NCEP	National Centers for Environmental Prediction
NLR	National Aerospace Laboratory (Nationaal Lucht- en Ruimtevaartlaboratorium)
NM	nautical miles
NOx	nitrogen oxides
OD	origin/destination
OI	operational improvement
ppm	parts per million
RCP	Representative Concentration Pathway
R&D	research and development
SEA	Societa per azioni ersercizi aeroportuali
SETX	Single engine taxiing/ electric taxiing/ hybrid taxiing
SOx	sulphur oxides
SO2	sulphur dioxide
SPC	La Palma Airport
SRES	Special Report on Emissions Scenarios
T	temperature
TAP	TAP Air Portugal (Transportes Aéreos Portugueses)
TCM	Trajectory Calculation Module
TGT	Trajectory Generation Tool
TMY	typical meteorological year
TOE	tons of oil equivalent

1. Introduction

1.1 ClimOP project

The aviation industry contributes to human-made emissions mostly by releasing carbon dioxide (CO_2), water vapour (H_2O), nitrogen oxides (NO_x), sulphur oxides (SO_x), soot, and sulphate aerosols. In terms of the influence human activities as a whole have in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, that is, the anthropogenic radiative forcing, the contribution from aviation has been estimated at slightly less than 5% [1]. At present, the Covid-19 crisis has caused an abrupt contraction of the activities in the aviation sector, which is still far from recovery and is not likely to return to 2019 levels before 2024 at the earliest [2]. However, once the current pandemic is overcome, air traffic is expected to resume its growth by 3 – 4% per year. This suggests that the aviation impact on climate will significantly increase over the next decades unless effective counteractions are planned and implemented.

Under the coordination of the Air Transport Action Group (ATAG), the aviation sector has long committed to cut its emissions and implement mitigation strategies to reduce its impact on the environment and climate [3]. This commitment has been recently restated despite the current crisis [4]. At the institutional level, the European Commission is supporting these efforts by promoting the research of innovative methods and technologies aimed at reducing the impact of aviation on climate. ClimOp is one of the four projects selected by the Innovation and Networks Executive Agency (INEA) within the action "Aviation operations impact on climate change" that pursues this purpose. These four projects, namely GreAT (Greener Air-Traffic Operations), ACACIA (Advancing the Science for Aviation and Climate), ALTERNATE (Assessment on alternative aviation fuels development), and ClimOp, focus on complementary aspects, respectively: innovative methods for a more climate-friendly air traffic management; a scientifically sound understanding of the aviation contribution to climate change; new fuels less dependent on fossil sources; and the identification and assessment of the most promising operational improvements to reduce the aviation climate impact and the evaluation of their impact on all the aviation stakeholders.

In the first year of the project, ClimOp made an inventory of the currently known operational improvements (OIs) and the available key performance indicators (KPIs) to quantify the effect of these OIs. Alternative sets of compatible OIs will subsequently be determined, and their impact on climate change will be assessed, taking CO_2 and non-CO_2 effects into account. In addition, in collaboration with the stakeholders in the consortium and the Advisory Board, ClimOp will evaluate the impact of these OIs on airports, airlines, air navigation service providers (ANSP), manufacturers, and passengers. As a result, ClimOp will develop a body of harmonised, most-promising mitigation strategies based on the alternative sets of OIs and will provide recommendations for target stakeholders on policy actions and supporting measures to implement the alternative sets of OIs.

1.2 Overview of Work package 1

The scope of Work package 1 (WP1) is to determine the OIs that have a large potential to mitigate the impact of aviation on climate. The first steps in this direction consisted of compiling an exhaustive inventory of all possible OIs that can be introduced, from the choice of ground equipment to changes in the allowed routes and specifically designed regulations to encourage climate-friendly practices [3], and identifying all possible KPIs that enable a quantitative assessment of these OIs [5]. These KPIs include climate impact metrics and metrics representing stakeholders' needs and priorities. The purpose of this approach is to ensure that requirements such as operation safety, practical feasibility, and long-term economic sustainability are taken into account in the analysis. The activities of WP1 continued with an analysis that associated each OI with the most relevant KPIs that capture its consequences for the climate and the involved stakeholders[1].

1.3 Deliverable D1.5 in the Project's context

The Deliverable D1.5 "Second iteration for the identification, assessment and selection of operational improvements" provides a second selection round of OIs listed in D1.3 as a basis for the current status of the study of these OIs and preliminary assessments carried out in WP2 and WP3.

Based on the discussions within WP2 and WP3 working groups, and considering the progress status of OIs by the end of D2.3, the consortium decided to continue further investigating the previously nine selected OIs for the second round of assessment. As a result, the second round of assessment would further investigate the current OIs on the list to enhance the results achieved by deliverable D2.3. However, the studies in this round may include modifications in OIs' scopes, workflows, and approaches to improve the results and broaden their scope, as reported in this deliverable.

Furthermore, at the end of this report, the consortium approach to integrating the nine OIs into three OI's deployment scenarios is discussed. Namely, we will consider trajectory-related, network-related, and ground operations categories, capturing the interdependencies between related OIs and combining results. We discuss the methodology proposed for each integrated scenario and the expected results presented in deliverable D2.4

2. Overview on the status of OIs in the first round

Analysing the results delivered by the first round of assessment in D2.3 [8], it was considered by the consortium that there are still promising opportunities for all OIs to broaden their study scopes. The ClimOP Consortium therefore decided to continue the investigation of this set of OIs and not to broaden the quantitative analysis to the other OIs initially described in D1.3 [5]. In particular, it was considered that the study of most OIs could be improved with further analyses, extensions of the models, or adaptations from the initial assumptions. Furthermore, it was considered to be benefitial to work on the integration of these analysis, considering new KPIs and combining these KPIs for a clearer comparison between OIs, before excluding OIs or considering new OIs.

The overview of OIs' progress status in the first round of assessment is presented in this section, while the modifications, improvements, and integration strategies are reported in the following two sections. One of the changes introduced in Sect. 3 of the present document is the merging of two inter-related OIs in the trajectory category. It was found that integrating "Free routing and dynamic flight planning in high-complexity environment/flexible waypoints" and "Wind/weather-optimised dynamical flight planning" would offer an opportunity to capture interdependencies between these two OIs. A detailed plan for this combination is reported in the section 3.2 under the name "Free routing and wind-optimised flight planning in high-complexity airspace ."

The progress is qualitatively assessed via a *status score*. On the one hand, these refer to models development and implementation, and on the other hand, model validation and KPIs calculation. The status score represents the progress in the following range:

Table 1: Status score guideline

Scores	Description	Model implementation	Validation / KPIs
1	**Not started or initial developments**	Major subroutines of the model are still missing or are under development	Results are not being computed yet
2	**Initial version**	Major subroutine(s) are implemented, but the scope is not complete	Results are incomplete and not enough for a validation
3	**Preliminary version**	Most of the subroutines are implemented, but there are still modelling elements to be added	A limited number of KPIs can be computed, or there is no validation effort yet.
4	**Advanced version**	All subroutines are implemented, but there is not yet seamless integration of these subroutines, or verification is not complete	Most KPIs can be computed, and the results are being compared with target values for validation
5	**Concluded or final developments**	All subroutines are implemented and running. Verification and the model robustness was concluded or is being concluded	All KPIs are or can be computed, and the model is validated

Workflow development and KPIs calculation will have a single value for the status score, which is the average score regarding all the works which have been done so far in these two aspects of the study.

Table 2: Status of operational improvements for trajectory-related OIs

Trajectory-related OIs				
OI	**Calculated KPIs**	**Remaining KPIs**	**Status score**	
			Model implementation	**Validation/ KPIs**
LOSL	• Emissions (CO_2, H2O, NOx, PM) • Fuel Flow • Contrail distance • ATR20 • Number of movements • Flight time • ASK (estimated) • Load factor (estimated)	• ATR100 • Routing efficiency • DOC • Acceptance • ATCo workload • Accident rate (airborne)	5	4 for climate KPIs 2 for non-climate KPIs
FREE	• Travel duration • Fuel consumption • CO_2 • Non-CO_2 emissions • Number of movements	• ATR20/ATR100 • ATC workload • Occurrence of Conflicts • Routing efficiency ASK/CASK	4	3
CLIM	• Flight time • Fuel Flow • CO_2 • Non-CO_2 emissions • Flight distance • Distance contrailling • Updated ATR20/ATR100 relying on aCCFs (V1.0)	• Flight time • Fuel Flow • CO_2 • Non-CO_2 emissions • Distance contrailling • Flight distance • Updated ATR20/ATR100 relying on CCFs	4	4 for climate KPIs 2 for non-climate KPIs
WIND	• Travel duration • Fuel consumption • CO_2 • Non-CO_2 emissions	• ATR20/ATR100 • ATC workload • Occurrence of Conflicts • Routing efficiency • ASK/CASK • Number of movements	4	3

Table 3: Status of operational improvements for network-related OIs

Network-related OIs				
OI	Calculated KPIs	Remaining KPIs	Status score	
			Workflow development	KPIs calculation
NETW	• ATR20 • Non-CO_2 emissions • Fleet utilisation • Flight time • Connection time • LF: RPK/ASK	• CO_2 • Airport traffic • Network traffic concentration • Network connectivity • Network morphology • Itinerary complexity	4	3
ISOC	• ATR20 • ATR100 • Emissions (H2O, CO_2, NOx, PM) • Sulphur content • Contrail distance • Movements • Flight time • Routing efficiency • ASK (estimated) • LF (estimated)	• Network connectivity • DOC • CASK • Mainten. cost • Aircraft on-ground time • ATCo workload • Pilot workload • Accident rate • Passenger acceptance	5	4 for climate KPIs 2 for non-climate KPIs

Table 4: Status of operational improvements for ground-related OIs

Ground-related OIs				
OI	Calculated KPIs	Remaining KPIs	Status score	
			Workflow development	KPIs calculation
SETX	• Fuel consumption • CO_2 • Non-CO_2 emissions	• Delay • Vehicle investments • Capacity	2	2
ELEC	• ATR20 • ATR100 • CO2 emissions • NOX emissions • Fuel flow • Maintenance cost • Refueling costs • Energy costs • Electric autonomy • Vehicle investments	• Accident rate • Airport capacity • Infrastructure costs • Social acceptance	4	3

Ground-related OIs

OI	Calculated KPIs	Remaining KPIs	Status score	
			Workflow development	KPIs calculation
INFR	• ATR20 • ATR100 • Annual electricity consumption per unit of volume • Annual thermal energy consumption per volume unit • Tons of CO2 emitted annually; CO2 emitted annually in PPM.	• Initial investment; • Annual economic savings thanks to reduction of energy consumption; • Time to return of investment; • Social acceptance; • Market acceptance; Political acceptance.	4	3

3. Description of OIs in the second round

3.1 Flying low and slow

3.1.1 Description

Higher flight altitudes come along with lower fuel burn and thus lower CO_2 emissions. Thus, CO_2-induced climate effects are reduced, because their climate impact does not vary with emission location. Nevertheless, the climate impact of contrails, water vapour, and NO_x varies with the altitude of their emission and can potentially be reduced by flying on lower levels. As this is associated with higher fuel consumption, an additional reduction of flight speeds can diminish the effect of higher fuel burn. This is analysed cumulated in terms of average temperature response (ATR), where effects of different emission species (CO_2 and non-CO_2) are summarised. To incorporate uncertainties due to different weather situations and long-term climatological changes, the study is divided into three sub-sections:

i. A basic study analysing the effects of the OI on the selected specific day of June 16th, 2018 (**Basic study**)
ii. A meteorological study analysing the effects of different weather situations of four representative days of 2018 (**Weather-based study**)
iii. A climate change study analysing the effects of long-term climatological changes for three subsequent 30-year periods (**Climate-based study**)

The first study presented in D2.3 shows a potential of reducing ATR20 by 4 - 7 % for North Atlantic flights in the selected basic case. For individual missions, reductions of 55% can be observed. In a second iteration presented, some adjustments to the basic study will be performed. Furthermore, uncertainties arising from different seasons (ii.) and climate change (iii.) will be investigated for the first time.

Besides the described climate impact of this OI, non-climate impact i.e. consequences for the involved stakeholders, need to be considered. While fuel consumption and thus the associated direct operating costs are expected to rise with lower flight levels and avoided fuel-optimal step-climbs, flight times will rise for lower flight speeds. This could potentially lead to lower passenger acceptance, affect the airlines' network and their costs and revenues. Furthermore, more flights on lower flight levels increase the utilisation of certain airspaces, which could affect the workload of air traffic controllers and impact airborne accident rates. Hence, non-climate impacts will be subject to the second modelling iteration, and results will be presented in D2.4.

3.1.2 Modifications

The modelling workflow of this OI has been presented in D2.2 and has been tried and tested since then. Modelling the base case is completed, results have been presented, and quality checks have been performed. Climate-related KPIs are calculated for individual missions, full flight plans and sub-sections. Limitations due to the taken assumptions and defined boundary conditions have been analysed and described in D2.3. Consequently, no major adjustments are planned with regard to the simulation chain and its assumptions.

Modifications planned in the second iteration of assessing the OI, will consist of the following:

- **Adjustments to the calculation of climate-KPIs:** The climate impact of this OI has already been quantified and described in the previous deliverable. Minor adjustments will be performed in a second iteration with regards to new algorithmic climate change functions (aCCFs), if available at this point. The functions, which are currently applied, are validated for the North Atlantic region only, but with a global flight plan applied, updates will assure more reliable results. Furthermore, ATR100 could also be calculated to complete the list of climate KPIs to be considered.

- **Calculation of non-climate KPIs:** The focus of the first assessment iteration was an analysis of the OI's climate impact. The next iteration will also take non-climate KPIs into consideration. In this context, the focus will be on changes in cost resulting from an implementation of the OI as well as changes from an air traffic management perspective, such as ATCo workload or accident rates. Cost calculation will be limited to direct operating cost (DOC), which can be derived from fuel consumption and flight times. Changes in air traffic and resulting KPIs will be analysed qualitatively, i.e. it will be estimated in what way these KPIs change due to an implementation of the OI.
- **Variability of results due to different atmospheric boundary conditions**: The second iteration on modelling operational improvements also focusses on the quantification of uncertainties within the simulation workflow. Therefore, different seasons with characteristic weather situations and long-term climatological changes will be considered by including different atmospheric data in the simulations. Flight plans will be adjusted to achieve comparable results, and results will be compared across the different observation periods. Further details on the assessment are presented in the following section 3.1.3.

3.1.3 Assessment process

The major work of the second assessment iteration focuses on the estimation of the uncertainties due to different meteorological or climate situations. Changes in atmospheric conditions that influence trajectories, emission quantities, and climate impact are expected to affect the climate impact of this OI. This will be quantified in two sub-studies described in the following.

Both investigations require adjusting the input data so that results are comparable across the different days of the seasons or long-term periods, respectively. The selection of seasonal days with characteristic weather has already been described in D2.2 and D2.3. For the identified four days, the flight plan is derived from EUROCONTROL's DDR2 data, which was already used for the base case. However, detailed point profiles are ignored and replaced by great circle (GC) connections as flown point profiles vary with every flight, among other things, because of different meteorological conditions or airspace capacities. A common flight scenario is selected from all four available days (one per season), which consists of all those flights with the selected long-haul aircraft (A330-243 and B777-300ER) that are performed at least once on all selected days. The resulting 157 flights are used for further analysis (see Figure 1). The corresponding flight levels, as well as departure times, are derived from the available EUROCONTROL data. To avoid using synthetic flight data, cruise flight level and starting time are sorted ascendingly, and the middle value is selected. Details on the weather-based study are presented in section 3.1.3.1. For the climate-based study, the identical flight plan is applied, and further description of the modelling workflow is provided in section 3.1.3.2.

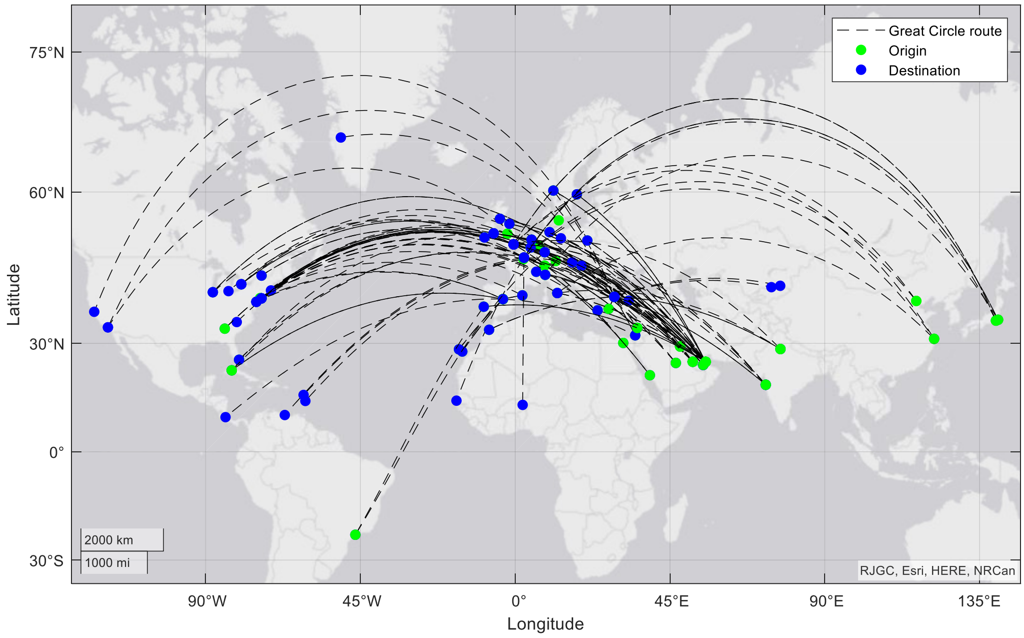

Figure 1: Flight plan for meteorological and climate change studies

3.1.3.1 Weather-based study

The modelling process for the study focussing on the influence of different seasons and thus different meteorological boundary conditions is displayed in Figure 2. The derived flight plan and the atmospheric data for the selected representative days is required as data input. Atmosphere characteristics for the respective days are provided by ECMWF reanalysis data and utilised in 3hr time steps so that eight different atmospheric datasets are considered per selected day. Further technological assumptions and boundary conditions equal the basic case described in detail in D2.3 (e.g. BADA4 performance data, average European load factor, spatial interpolation). On this basis, trajectories are calculated while cruise flight levels and speeds are varied systematically. Detailed trajectory data enables emission calculation and consequently calculation of climate impact with aCCFs.

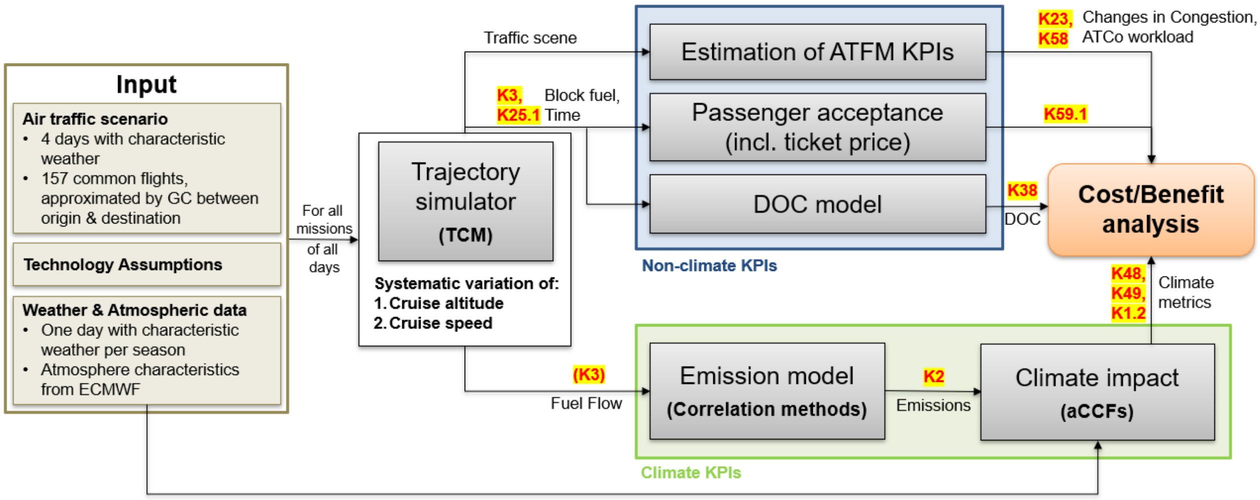

Figure 2: Model workflow for weather-based study

The main goal of this study is to quantify variations in climate impact (i.e. ATR) of this OI caused by different meteorological situations. Thus, the determination of non-climate impact KPIs is not in the focus of the assessment process. The stakeholder impact, such as passenger acceptance, influences on costs and air traffic related consequences, will be estimated qualitatively and compared to the base case. The results can be brought together in a final cost-benefit analysis.

3.1.3.2 Climate-based study

The simulation workflow to quantify variations from long-term climate change is presented in Figure 3. Due to its focus on variability resulting from climate changes, it is reduced compared to the other sub-studies of this OI. Flight plan data is equivalent to the weather-based study, and technology assumptions equal the base case (e.g. in terms of load factor or consideration of BADA4 performance data). Applied atmospheric data changes: Instead of considering ECMWF reanalysis data from selected days and times, a multi-model mean following RCP 4.5 is calculated for three thirty-year-long periods:

- from 1991 – 2020,
- from 2021 – 2050, and
- from 2051 – 2080.

This leads to synthetic atmospheric characteristics that are representative of the respective climatological period. On this basis, detailed trajectories are calculated, and emission quantities are determined.

Furthermore, contrail formation along these trajectories is analysed. Climate changes and potential rises in temperature are expected to shift contrail forming regions. To investigate this, the thermodynamic possibility of contrail formation (e.g. Schmidt-Appleman criterion) and persistence criteria (i.e. contrail formation in ice supersaturated region) are evaluated along the different trajectories [6]. Contrail distances for different flight levels and missions are quantified, and on this basis, the effects of flying low and slow on contrail formation can be assessed. This can be combined with changes in emission quantities and fuel flow to analyse the variability of climate impacts of the OI. Climate impact KPIs in terms of ATR is not evaluated because of missing validation of aCCFs for future climate situations.

This study's main goal is to quantify uncertainties in e.g. fuel flow, emissions and flight time deriving from long-term climate changes on average temperature response in general and contrail formation in particular relative to the climate reference period 1991 - 2020. Hence, non-climate KPIs will not be in focus. To ensure a reliable implementation of the OI, changes in fuel consumption and flight time will be calculated as part of the trajectory simulation and enable an approximation of resulting costs.

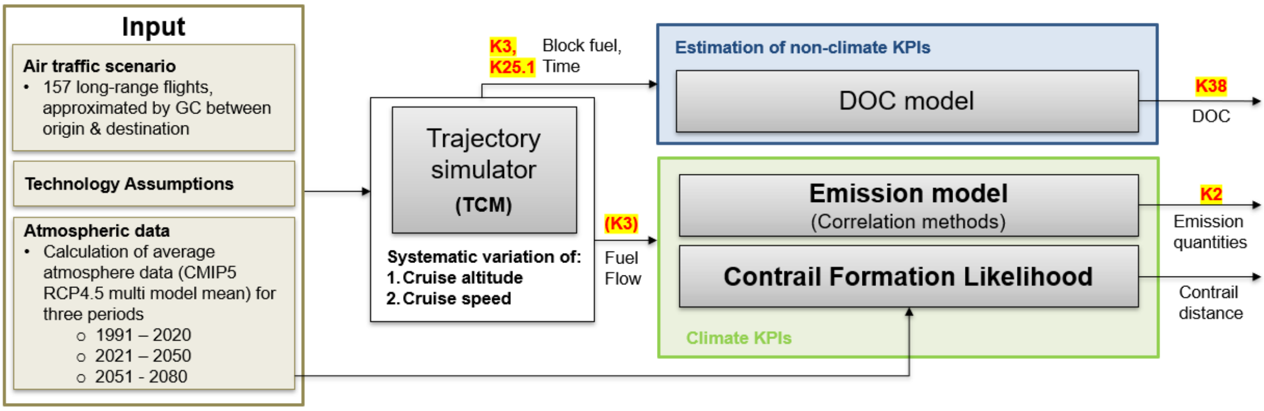

Figure 3: Reduced model workflow for climate-based study

3.2 Free routing and wind-optimised flight planning in high-complexity airspace

3.2.1 Description

This OI covers the both free routing in high-complexity environment and wind/weather-optimised dynamic flight planning studied in the first round of assessment. We plan to merge these two OIs and evaluate them together with the same traffic scenario and model components to improve comparability and analyse the impact of flying direct routes and wind/weather-optimized routes in free route and high-density airspace.

The free routing concept aims to remove the constraints originating from the standard airways and provide an opportunity for flying more efficient routes to reduce fuel consumption and environmental impacts. In this study, we mainly focus on the implementation of the concept in high-density en -route airspace in the ECAC area. As the first case study, the free routing concept is implemented by defining the shortest paths between entry and exit points as the preferred routes. As the second case study, the wind/weather-optimised flight planning is implemented in free route airspace. This planning strategy aims to optimise the flight trajectory according to the defined operational costs by exploiting the wind/weather information to improve efficiency. According to the defined operational costs, fuel consumption, CO_2 and non-CO_2 emissions can be reduced.

3.2.2 Modifications

The same workflow presented in D2.3 for the wind/weather-optimised flight planning will be used in the second round of assessment without any modifications in the trajectory simulator and optimisation method. However, the wind model and fuel consumption constraint in the optimisation problem will be improved to enhance fidelity of the flight planning algorithm. Furthermore, some of the KPIs have not been assessed yet. The case studies of OI will also be evaluated using these remaining KPIs. The modifications in the model components and remaining KPIs are presented in the rest of this subsection.

3.2.2.1 Wind Model

In the optimisation problem, the wind model has been simplified using the linear functions according to longitude and latitude. This approximation is valid for some days, while it cannot capture the correct phenomenon in other days when the wind components change non-linearly. Therefore, the wind model presented in D2.3 will be improved by using high-degree polynomials to enhance the model generalizability.

3.2.2.2 Fuel Consumption Constraint

In the current model version, the fuel consumption constraint in the optimisation problem is obtained from the BADA3. However, the BADA4 presents an enhanced approximation to calculate the fuel consumption. We are planning to modify the corresponding constraint in the optimisation problem for fuel consumption according to the BADA4 to improve the fidelity of the optimisation process.

3.2.2.3 KPIs

The calculation tools for some KPIs have been already developed. The simulation environment and optimisation algorithm directly generate the travel durations and fuel consumption, while the CO2 and non-CO2 emissions are obtained using the developed emission model described in D2.3. The number of movements in the airspace has been obtained for the free routing concepts, while it will also be generated for the wind/weather-optimised flight planning. These KPIs will be recalculated after modifying the aforementioned model components of the optimisation algorithm to present the final results. The remaining KPIs that will be evaluated in D2.4 can be listed as ATR20/ATR100, ATC workload, routing efficiency, ASK/CASK, and safety, as occurrence of conflicts. ATR20/ATR100 will be obtained using the algorithmic climate change functions (aCCFs). Appropriate estimation tools will be developed to calculate their values for the rest of the KPIs. Routing efficiency will be estimated as the divergence from the original flight distance in the base-case scenario. And, ATC workload will be approximated using the traffic density and potential interactions in vertical and horizontal planes as presented in the study [12].

3.2.3 Assessment process

The assessment process is based on comparing the simulation results of the base-case scenario and the defined case studies for this OI. The overall workflow is illustrated in Figure 4. The improvements in the model components of the optimization problem and the additional KPIs will not affect the assessment process. The same assessment strategy defined in D2.3 will be used. However, there will be three different scenarios to evaluate the free routing with direct routes and wind-optimised flight planning together. The first scenario is the base-case scenario in which the trajectory simulator simulates the traffic according to the defined flight plans for the real operation. The second scenario refers to the implementation of the free routing concept with direct routes. In this scenario, the air traffic service routes are removed, and the flight plans are modified using direct routes between entry and exit points in the airspace. The trajectory simulator simulates the traffic using the new flight plans to obtain the flown trajectories in the free routing concept with direct routes. Next, the developed planning algorithm is used to generate an optimised route between entry and exit points of the airspace for each flight in the third scenario. There is no route constraint in the wind-optimised flight planning except the initial and final waypoints, so the third scenario can be considered as the implementation of the free routing concept with optimisation-based planning algorithm. Then, the obtained trajectories in each scenario are used to calculate the KPIs. The impact of the different implementations of free routing concept on the stakeholders such as air traffic controller, airline, passenger, and the environment is analysed using the calculated KPIs. The second and third scenarios have been implemented independently as different OIs in D2.3, and the preliminary results have been presented. We plan to evaluate them as different scenarios in the same OI by using same aircraft performance parameters and model components in the second round of assessment. We will also focus on the same en-route airspace specified in D2.3.

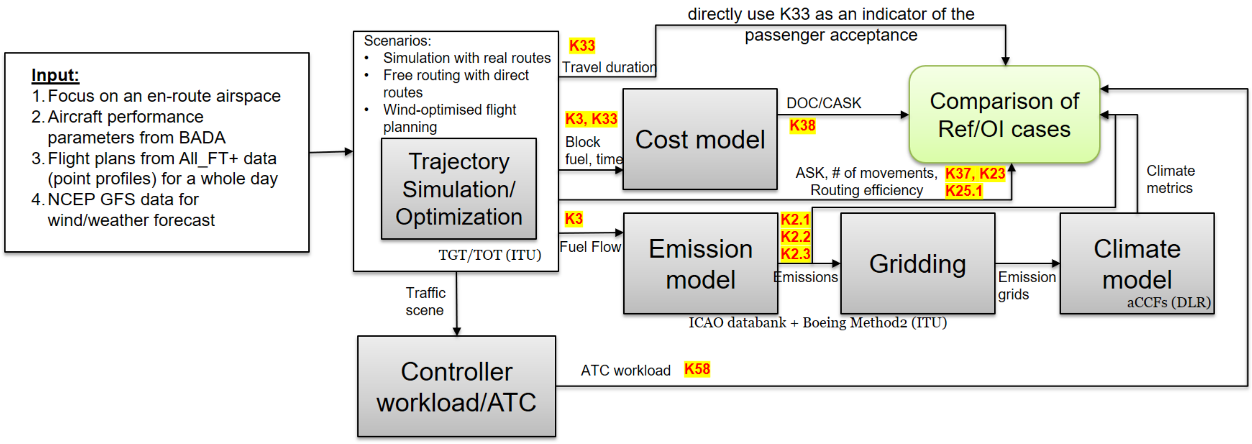

Figure 4. Model workflow for OI of "Free routing and wind-optimised flight planning in high-complexity airspace"

3.3 Climate-optimized flight planning

3.3.1 Description

Climate-Optimized Flight Planning (CLIM) aims to identify alternative flight routes that have a lower overall effect on climate by avoiding regions of the atmosphere that are particularly sensitive to aircraft emissions. In phase 1, this OI was assessed by applying an expanded air traffic management (ATM) system relying on algorithmic climate change functions (aCCFs). A comprehensive study was conducted for European airspace that examined individual mitigation gains as well as total combined mitigation gains based on single flight analysis. Such combined mitigation gains are based on the fact that the mitigation potentials for individual city-pairs vary depending on the atmospheric characteristics of the airspace where the flights are executed. Under a systems approach, a common threshold for mitigation potential is established and expressed as climate impact mitigation relative to the associated penalty in costs. By applying this common threshold to individual flights, the flights with higher mitigation potential will contribute more to mitigation performance (since they provide "cheap mitigation performance"), while the flights with low mitigation potential will contribute less (since they only provide "expensive mitigation performance"), resulting in efficient implementation.
The one-day case study in phase 1 used data which has been published in Matthes et al. (2020) [19] and Lührs et al. (2021) [20] and refers to a winter situation on 18 December 2015, which was characterized by a contrail forming region over the central European Airspace on that specific day.

In Phase 2, the CLIM OI will examine specific traffic samples from the 2018 reference year and scenarios that include geographic regions that have been newly characterized in terms of their climate effects. For these regions, 4-dimensional climate change functions (CCFs) are derived to determine the effects of contrail formation in particular, by performing comprehensive global atmospheric simulations using a Lagrangian submodel ATTILA in the modular Earth-System model EMAC. The application of these novel climate change functions in Phase 2 will allow comparison of climate effects induced by contrail and contrail cirrus formation with estimates based on the application of aCCFs (developed for the North Atlantic Flight Corridor) that were used in the previous phase 1.

3.3.2 Modifications

The same modelling workflow of this OI that has been presented in D2.2 [7] will be used in the second round of assessment with the implementation of the novel spatially and temporally resolved information on climate effect induced by contrail and contrail cirrus formation. Alternative climate-optimized trajectories were identified for a specific case study, results were presented for both individual trajectories and the Top 2000 routes in Europe, and quality checks were conducted. For non-climate related KPIs the flight time was analysed in D2.3 [8]. Therefore, the overall simulation chain remains the same, but the CCFs implemented will be updated.

Changes planned in the second iteration of the OI assessment include the following:

- To provide meteorological data of the OI CLIM simulation, we use meteorological data provided by ECMWF. In the previously published one-day case studies (Matthes et al. (2020) [19]), ERA-5 reanalysis data were used to estimate mitigation potentials based on a realistic representation of real atmospheric conditions as they prevailed on that specific (historical) day. Such numerical reanalysis model data also rely on assimilation of observational data to improve numerical weather prediction with observations. Another option for OI CLIM assessment would be to use historical forecasts to simulate and identify alternative trajectory options using knowledge available prior to departure. This means that no observational data would be incorporated into the meteorological data. Such reanalysis data are also used in the development of climate change functions because the EMAC global chemistry-climate model can be run in a "nudged" mode, using certain dynamics from real-world situations as boundary conditions to produce the meteorological situation that prevailed on a given day.

- Novel climate change functions are used to optimize the trajectories instead of relying on algorithmic climate change functions derived from data for the North Atlantic Flight Corridor. On the one hand, this will enable to provide an updated estimate of the mitigation potential of alternative trajectories which avoid those regions of the atmosphere which are sensitive to aviation emissions, i.e. contrail forming regions. On the other hand, this will help to understand how good the aCCFs estimates (prototypes) are, and it might help to verify possible CCFs applications in future studies.

3.3.3 Assessment process

In this phase, the CLIM OI will use novel data to describe the climate impact of contrail and contrail cirrus in overall trajectory optimization experiments. These more detailed contrail-induced cloudiness climate functions (CCFs) will provide an updated estimate of mitigation potential when minimizing climate impacts by identifying alternative, climate-optimized aircraft flight paths. In order to expand the geographic scope to other regions than the North Atlantic Flight Corridor, we develop and analyse climate change functions for different regions with a comprehensive Lagrangian approach. To understand the impact of key atmospheric parameters such as temperature or humidity on contrail formation, the difference between NAFC regions and the European Airspace will be briefly discussed.The relevance of using these new CCFs will be evaluated by comparing the results to the Phase 1 approach, which used the aCCFs developed for the North Atlantic Flight Corridor.

The Trajectory Optimization Module (TOM) which uses optimal control techniques in order to determine climate optimized aircraft trajectories, is used similarly to the previous phase to determine fuel-optimal trajectories as well as alternative trajectories. For this study, the optimation will be based on CCFs instead of the algorithmic climate change functions.

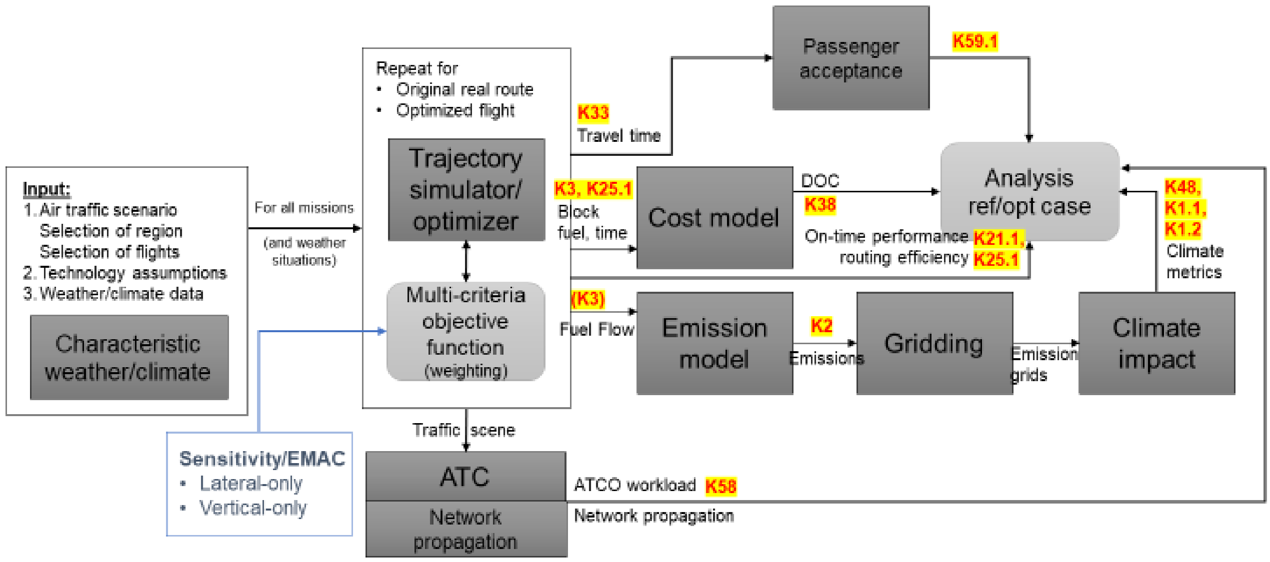

Figure 5. *Workflow for OI Climate-optimized flight planning (CLIM)*

3.4 Strategic planning: merge/separate flights; optimal network operations

3.4.1 Description

Airline network planning is a strategic decision and directly affects market share, operating cost, and passenger demand. Currently, airline networks are designed based on profit and demand-capturing intentions. These objectives contribute to airline revenue but are not necessarily efficient in operation climate impacts. There would be a trade-off between total airline revenue and the climate impact of flights when designing an airline network. Airlines tend to have greener operations and networks concerning fuel consumption and emission production. Achieving such a goal may need to renounce a part of their revenue.
With this OI, the goal is to reduce annually climate impacts (specifically ATR20) of airlines further than exchanging the cost-optimal trajectory with ATR-optimal ones. A Pareto-frontier diagram will be introduced to visualise the trade-off between monetary and climate-related objectives.

3.4.2 Modifications

In general, we plan to incorporate two categories of modification in the workflow along D2.4. Firstly, the network planning configuration changes that will take place mainly within the AOMAS[1] model. The main change is related to the airline market share assumption. In the D2.3 we assumed that airlines have a constant market share regardless of their frequency. Although, there is S-shaped curved representaing the relation between the frequency offered in each OD pair and the market share. Secondly, improvements in climate impact and climate response modelling . Also, adding modules that will enhance the results from AirTraff. The following subsections will elaborate more on these modifications.

3.4.2.1 Airline-related

Airline market share
The current demand modelling module within the AOMAS uses static passenger demand for all OD pairs. This will be improved to capture the competition and flight frequency demand dynamics within each OD demand pair. In particular, the airline market share module is being introduced to consider that the market share per airline changes according to an S-shaped curve, capturing the relation between the frequency offered in each route by each airline.

Additional KPIs and KPAs
A set of additional KPIs and KPAs will also be considered in order to investigate this OI further and provide additional aspects to compare the OIs in WP3. Namely, "Network connectivity", capturing the number OD pairs that could be flown within the network, "Network concentration", measuring geographical concentration of spoke airports, “Passenger traffic volume” and "Average load factor" in the network which will be added in D2.4.

3.4.2.2 Climate-related

CO_2 emission
Currently, AirTraff is utilised to calculate the climate-related KPIs for this OIs. It was developed to measure non-CO_2 emissions and their associated ATR20, so there is no CO_2 emission in the output. State-of-the-art studies use a linear estimation of CO_2 based on the amount consumed fuel. A similar approach will also adopt to calculate the CO_2 in this OI.

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[1] Airline operation multi-agent system

Representative days revision
ATR is very sensitive to the meteorological condition of the emission. Measuring the potential improvement in worst and best case weather scenarios would provide a more reasonable overview of feasible results. With this regard, a design of experiment (DOE) method will be used to find the uncertainty range of calculated ATR and emission values.

3.4.3 Assessment process

In contrast to airline-related modifications, climate-related ones affect the workflow and assessment process. The updated approach in the modelling is depicted in the Figure 6. As described in the previous section, airline-related changes are within the AOMAS module, but the climate-related modifications need an extra stage regarding the uncertainty analysis and DOE right after the AirTraff. In this stage of the workflow, a systematic weather analysis will be carried out to estimate the potential bounds of climate-related KPIs. A detailed description and results of modifications will be presented in the D2.4.

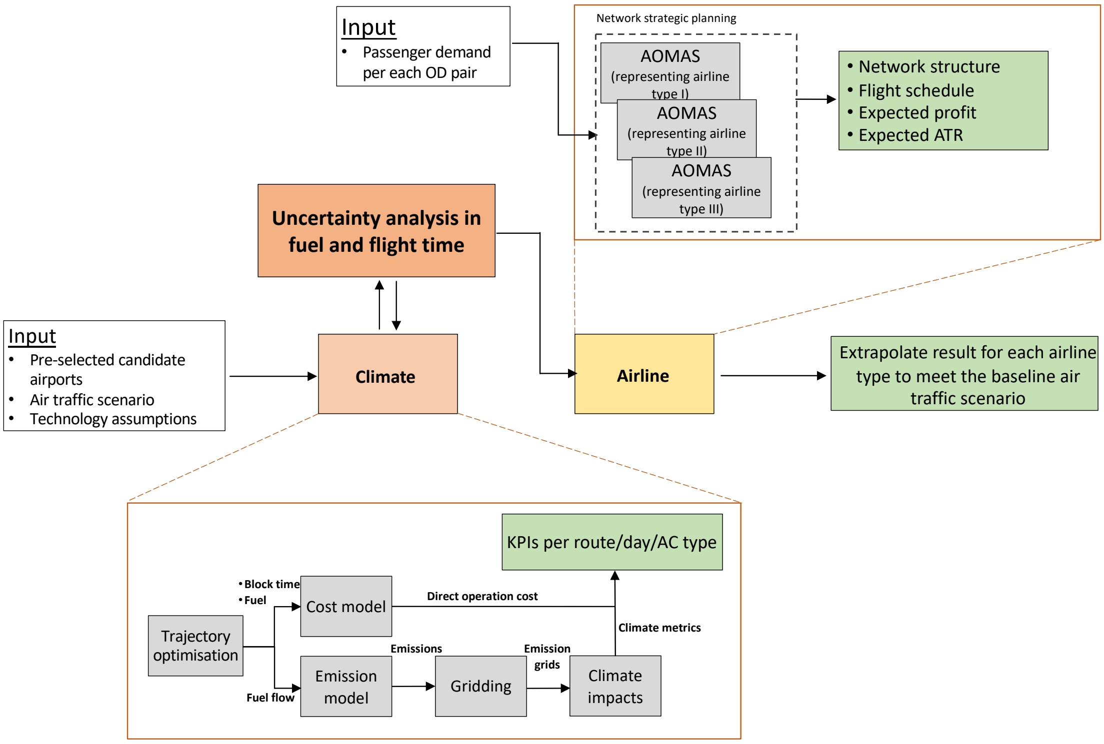

Figure 6: Updated workflow for OI of 'Strategic Network Planning'

3.5 Climate-optimised intermediate stop-over

3.5.1 Description

The concept of intermediate stop operations (ISO) aims to reduce fuel consumption and/or climate impact by reducing the amount of fuel to be carried on a flight. Instead of performing a direct long-haul flight, the mission is interrupted by an intermediate landing for refuelling. Less fuel has to be carried, weight and thus fuel consumption can be reduced. While the fuel-saving potential of this concept has been confirmed in previous studies [10],[11], an optimisation with regards to climate impact is the focus of this study in ClimOP. In addition, fuel-optimised ISO typically leads to higher flight altitudes due to reduced weight and thus, emissions are emitted in more climate-sensitive areas and lead to higher climate impact (Figure 7). A limitation of flight altitudes to reduce climate impact is an additional aspect of this study.

Results from the first iteration presented in D2.3 [8] show a climate-mitigation potential of more than 6 % with regards to ATR20 and ATR100, which is associated with a detour of approx. 4% and an additional flight time of 11%. Fuel consumption increases by 3% compared to the non-stop reference case. A second iteration will concentrate on additional improvements due to reduced flight altitudes, and a detailed comparison between fuel-optimal, and climate-optimal ISO will be performed. Furthermore, a quantification of non-climate KPIs (e.g. network effects, cost) will be analysed, and a fleet exchange with aircraft designed for shorter ranges will be assessed.

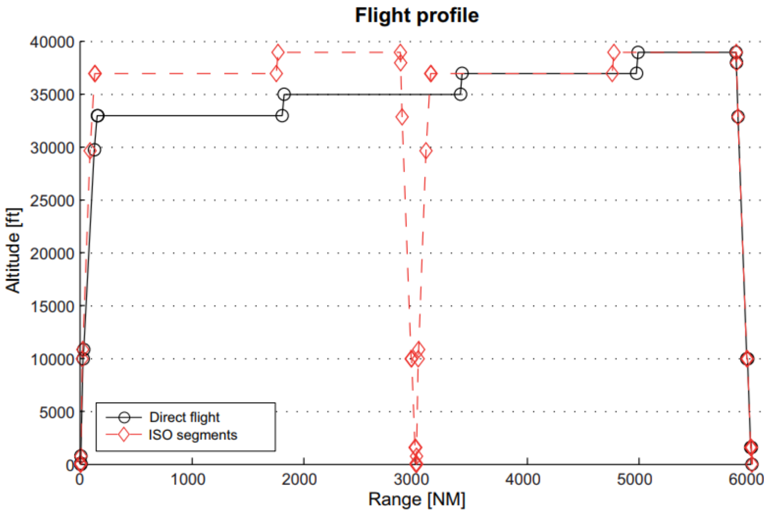

Figure 7: Higher flight altitudes of ISO compared to direct flights [11]

3.5.2 Modifications

The modelling workflow of this OI has been presented in D2.2 and D2.3 and was applied in the first modelling iteration. The reliability of results and suitability of the modelling workflows has been confirmed so that no major changes are planned for the second iteration. Also, boundary conditions and limitations due to the taken assumptions (such as an average European load factor or ISA) are not expected to change (see [8], Chapter 2.6.4 for more details). Nevertheless, some minor adjustments are planned with regards to an extended evaluation of the results and inclusion of non-climate aspects into the analysis, i.e.:

- **Extension of considered flight altitudes:** Lower aircraft mass due to reduced fuel required leads to higher fuel-optimal flight altitudes and, thus, potentially to emissions in more climate-sensitive areas and a higher climate impact of the respective mission. The already performed analyses ignored this fact by assuming a constant flight level for both fuel-optimal and climate-optimal ISO missions. An in-depth assessment will analyse this by additionally considering fuel-optimal step climbs to achieve further fuel savings as well as further possible flight levels to additionally improve the climate impact. In this course, a more sophisticated comparison between fuel and climate optimal missions will be possible, and the impact of different flight levels will be assessed.

- **Climate impact calculation of the aggregated flight schedule:** The selection of ISO airports according to optimal climate impact was performed on a flight level basis, i.e. ATR was calculated individually for every possible ISO mission and the one with the lowest impact was selected. The total climate mitigation potential for the full global flight plan was estimated by linearly aggregating the individual missions' climate response. In a second iteration, this will be performed more differentiated by feeding the full flight plan to DLR's climate chemistry model AirClim, so that saturation effects can also be considered.
- **Replacement of aircraft types:** An additional aspect of this study will be a replacement of the long-range aircraft used for the direct flights by aircraft optimised for shorter distances in the ISO missions. In this context, multiple aircraft will be used to ensure that the same amount of passengers can be covered. The effects will be analysed in a case study covering a sub-sample of the full flight plan.
- **Evaluation of non-climate KPIs:** The first iteration focuses on quantifying the climate impact of the OI, whereas the next round will also take non-climate effects into consideration. In this context, changes in time, fuel consumption[2], and ATR will be combined, while the trade-offs are analysed. Furthermore, DOC will be estimated, and the impact on an airline's network will be analysed.

3.5.3 Assessment process

The modelling workflow for the second iteration of the ISOC is illustrated in Figure 8. The aspects that will be in focus are highlighted in blue. Results will be presented in D2.4. Besides new aspects that will be investigated (i.e. replacement of aircraft types), the next iteration will focus on the evaluation of non-climate KPIs as well as a more differentiated comparison between fuel-optimal and climate-optimal ISO missions in terms of climate impact, the influence of different flight levels and cost aspects. Furthermore, network effects will be analysed in coordination with the other network-related OIs such as NETW.

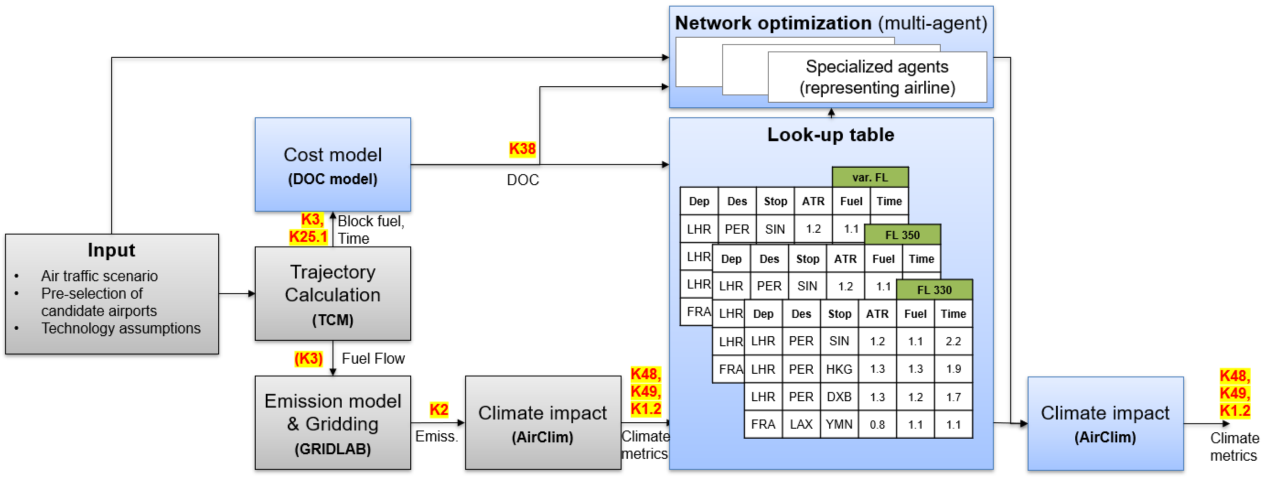

Figure 8: Focal assessment steps (in blue) for the second iteration of climate-optimised ISO

[2] Fuel cost counts for the main part of the direct operational cost of a flight. Also, changes in flight time affect utilisation rate of the fleet and hence the revenue an aircraft can make in a week/month (cf. [8], Sect. 2.6).

3.6 Single engine taxiing / E-taxi and hybrid

3.6.1 Description

This operational improvement focuses on reducing fuel used for ground movements by using either a single engine or an alternative method propel the aircraft on the ground. One of these alternatives is using an on board electric system using wheel based electrical motors, which does add wait and thus fuel burn in cruise. Savings are mostly expected on short sectors between large airports.The other option is a towing vehicle thatis airport based and tows the aircraft in the ground. While towing does not add weight, usage is dependant on the availability of tow trucks at each airport. Large airport are expected to more likely to have a large enough fleet than smaller ones.

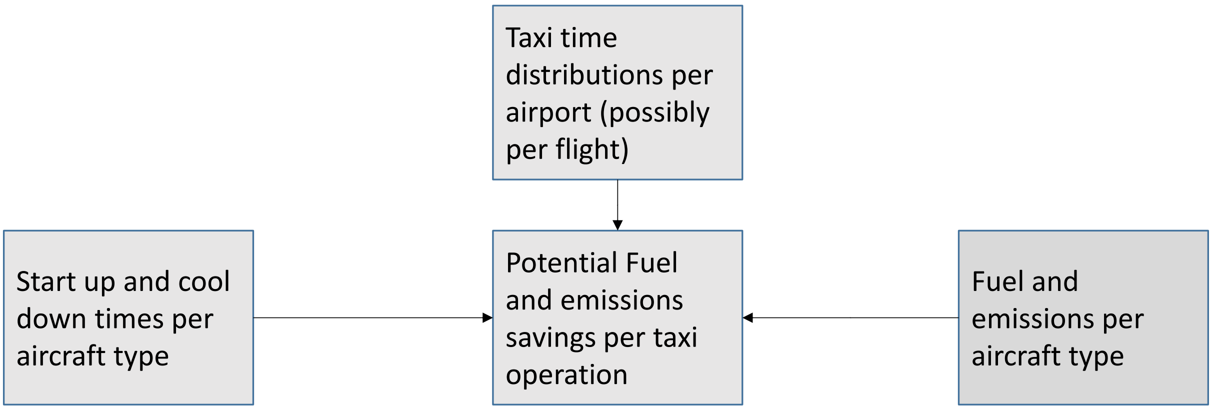

Figure 9: Saving per aircraft ground movement

3.6.2 Modifications

In the second round of assesment work will move towards a more global assessment of the potential of implementing these methods.

For the savings per aircraf per ground operation, shown in Figure 9, this means acquiring data for most representative aircraft types and data on taxi times for most airport. The most common aircraft types will use speicific data, while smaller, less common ones will be using more generic values.For smaller origin and destination only airports with a single runway a baseline value can be taken for the taxi time.

The result of this step will be a table for each aircraft type and airport combination speicifying the nomal fuel consumption and emissions during taxi, the fuel consumption and emissions during single engine taxi, the fuel consumption during eTaxi of the APU under increased load and the fuel consumption of being towed of the APU.

For all optimisations, the objective is primarily saving aviation fuel, though emission impact will be calculated using the ICAO emissions database.

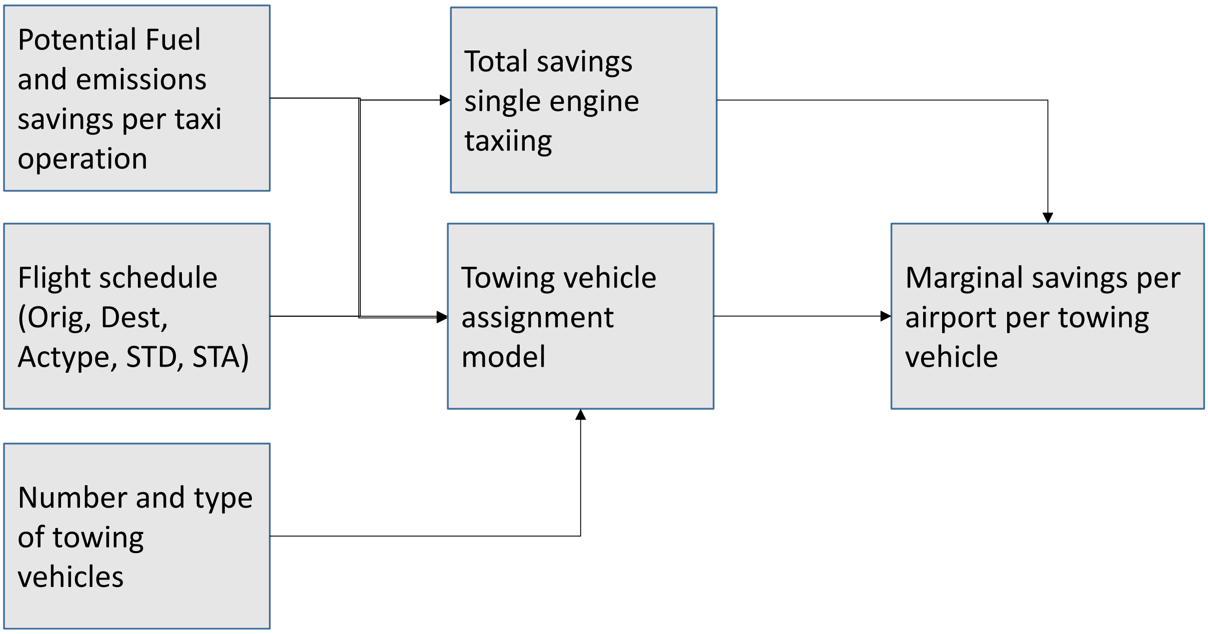

Figure 10: Savings for towing

For towing, as optimisation will be done starting at the largest airports looking at the required savings per tow truck for an average peakday using an assignment model, as shown in Figure 10. Most likely a minimum required marginal fuel saving per two truck will be set to get comparable numbers on the environmental impact for all analysed airports.

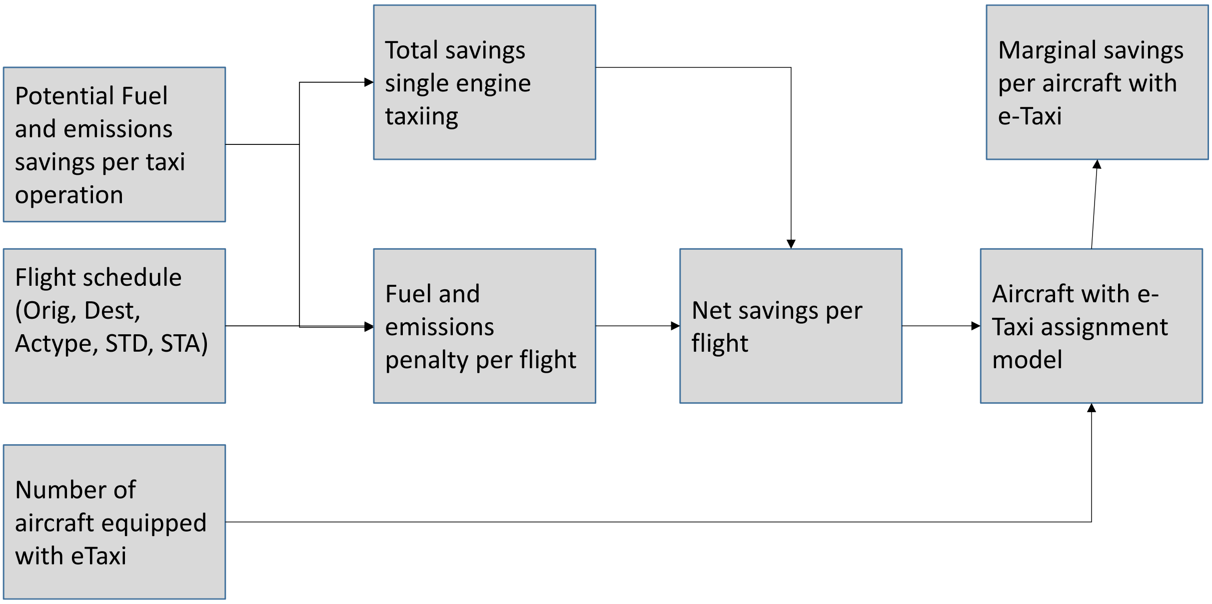

Figure 11: Savings for eTaxi

For eTaxi an analysis, Illustrated in Figure 11,will be done starting with the largest airlines (both hub and spoke as well as low cost) and a limited number of short to medium range aircraft types. A minimum required fuel saving per aircraft om a peakday will be set to get comparable results per airline and aircraft type. A minimum number of eTaxi equiped aircraft per airline and aircraft type will need to be determined.

3.6.3 Assessment process

- Select the aircraft types and airline with most potential for eTaxi
- Select the busiest airports for towing
- Calculate the potential saving per aircraft operation and airport combination
- Extract / create epresentative peakday flight schedules for analysis per airport or airline.
- Run the assignment model per airport starting with the busiest airports
- Run the assignment model per airline starting with the largest airline and an aircraft type
- Determine suitable minimum number of tow trucks per airport
- Determine suitable minimum number of eTaxi equiped aircraft per aircraft type and airline
- Determine savings potential per solution type.

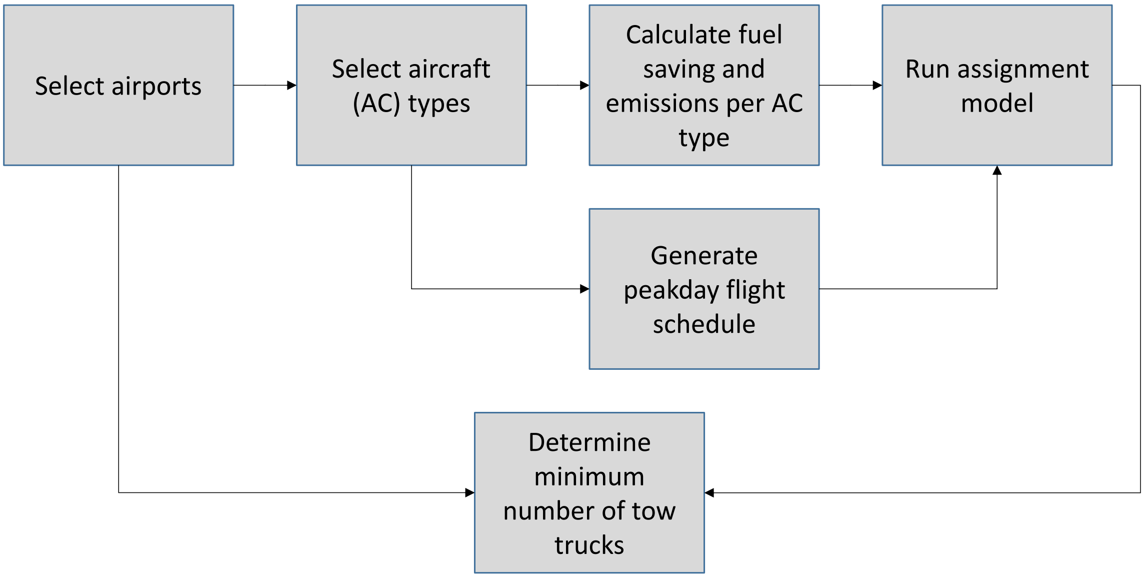

Figure 12: Workflow for towing

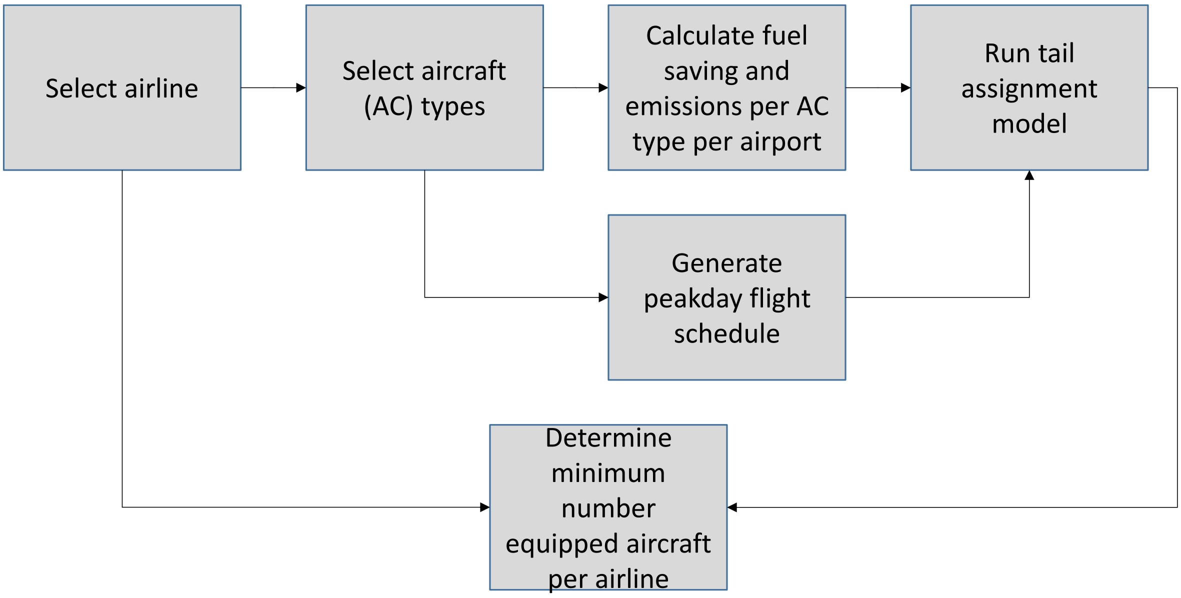

Figure 13: Workflow for eTaxi

3.7 Electrification of ground vehicles and operations

3.7.1 Description

This OI explores the climate impact of replacing the current fleet of fossil-fuel vehicles used at airports for Ground Support Equipment and Operations with an equivalent fleet of electric vehicles. To quantify this impact, we developed a model that determines the overall emissions of the current fleet and compares it to the total amount of emissions necessary to generate the electric energy to power a fully electric fleet. Our approach is described in detail in previous deliverables [6], [8]. We summarise the main steps of our methodology as follows. First, we analysed the data made available by SEA about the ground fleet of the Milan Malpensa and Linate airports. We classified the vehicles based on their size (small, medium, and large) and calculated each category's annual mileage and fuel consumption. From the fuel consumption, we computed the annual emissions of different GHGs (CO_2, SO_2, NO_X, and CO). Subsequently, we created a synthetic fleet of electric analogues of the existing vehicles, and we calculated the energy required to power this fleet. We computed the emissions associated with the energy generation by different sources: coal, petrol, gas, and an average European mix of generation sources[13], [14]. These emissions are used to compute the global change in atmospheric CO_2 concentrations and the corresponding average temperature response at 20 and 100 years (ATR20, ATR100) using the IPCC 2001 Climate Change Report [15]. The preliminary results of this analysis are shown in deliverable D2.3 [8]. Considering only the two main Milan airports, the electrification of the entire ground fleet would reduce the emissions of GHGs by a factor between approximately 1.2, if the energy generation source is coal, and 6.3, if the average European mix of generation sources is considered [8]. Lower GHG emissions correspond to a reduction of the average temperature response by about 84% compared to the current scenario for the two Milan airports combined. The model can extrapolate the results to any other airport in Europe using the number of annual flight operations as a proxy to determine the number and size distribution of the ground fleet of that airport. The underlying assumption is that the relation between flight operations, ground vehicle numbers, and size distributions is linear.

3.7.2 Modifications

The planned improvements to the analysis of this OI are presented as follows:

- Refine the technique to generalise the results obtained for the two Milan airports by gaining access, if possible, to data about the ground fleet of other European airports. For this purpose, we are currently contacting the members of the project's Advisory Board to explore their availability to share data that can benefit the project.
- Calculate the cumulative impact of GHG emissions and ATR20-ATR100 in electrifying the ground fleet and operations in the most trafficked European airports.
- Estimate the uncertainty associated with the results produced by our model, in particular, to determine whether there can be scenarios in which electrification is not convenient from the point of view of the climate impact.
- Calculate a cost-benefit analysis of the fleet upgrade, considering the refuelling costs (€/km), the maintenance costs, and the investment required to purchase the electric vehicles.

3.7.3 Assessment process

The assessment of the climate impact of this OI will be performed as summarised in Sect. 3.8.1 and as thoroughly described in previous deliverables [6], [8]. In particular, a cost-benefit analysis for this OI will be performed by considering the purchase and maintenance costs of the current and new vehicles, the costs of fuel and electric energy, and the time span for the transition of the fleet from the current composition to fully electric. As described in deliverable D2.1 ([6] sections 2.8.2 and 3.1), literature projections of the price evolution of vehicles and fuels over the next decade are used.

Although indirectly, the cost-benefit analysis will also try to account for the change in the airport's reputation among passengers and citizens as a result of the commitment to reduce the emissions, according to the results of the passenger survey presented in Sect. 3.2 [6].

Several sources of uncertainty need to be taken into account to estimate the overall uncertainty associated with our model predictions about the climate impact of this OI. These include, for example: the classification of all vehicles in three classes with well-defined mileages and fuel consumptions, which is a fundamental element for the scalability of the model but it also is a simplistic representation of the real usage of the vehicles; the uncertainties in the conversion factors between fuel consumption or energy generation and GHG emissions; the uncertainties in the estimates of energy demand based on the mileage of electric vehicles. In the next round of assessment, we will calculate two scenarios combining, alternatively, the most conservative and the most favourable set of assumptions to evaluate the extent of these uncertainties in terms of the expected climate impact of the electrification of the ground vehicles.

3.8 Upgrade of the airport infrastructure according to energy efficient criteria

3.8.1 Description

Airport buildings consume a significant amount of energy to maintain comfortable occupancy conditions, which require space heating and domestic hot water preparation, ventilation and air conditioning/cooling, power supply for lighting, and other airport systems (e.g., elevator). The improvements in the infrastructure according to energy-efficient criteria are expected to significantly reduce the energy consumption of airports, and hence their GHG emissions. Applying energy-efficiency measures to the airport infrastructure is immediately feasible and is effective over the long term. However, the initial investment is rather demanding, and the renovation works might cause problems for the operations, especially when they are carried out at terminals.
The assessment of this OI focuses on analysing the change in CO2 emissions thanks to the application of a selection of energy-efficiency measures on the office buildings of European airports. The energy consumption of a conceptual office building is simulated with the open-source software of the US Department of Energy, EnergyPlus[16]. The considered energy-efficiency measures are implemented to calculate the reduction of energy consumption with respect to the baseline. Then, the results are generalised to assess the effect throughout Europe by considering the hypothesis that the energy demand is proportional to the aircraft movements to and from an airport. The calculation is repeated for future climate conditions to estimate the effectiveness of this OI in reducing climate change.

3.8.2 Modifications

For *the second assessment*, we plan to improve the results presented in D2.3 as follows.

ATR20 and ATR100 definition

ATR is currently calculated on the basis of the reduction in temperature increase due *to* energy savings. The latter is estimated by applying the *following* formula from the IPCC report 2001 [17]:

$$\Delta T = 1.66\, ln\left(\frac{C_o - \Delta C}{C_o}\right)$$

where ΔT is the temperature change corresponding to the effect of this OI alone, C_o corresponds to 407.4 ppm and is the global value of CO_2 in ppm in 2019, and ΔC is the reduction in CO_2 due to the applied energy efficiency measures. The idea behind this formulation is to isolate the contribution of this OI to climate change from all the other human activities. However, its limitation is that it cannot be expressed as a percentage of the business-as-usual case, as it implicitly includes the variation with respect to it.

In the second assessment, ΔT will be calculated for the emissions related to the energy consumption of a conceptual office building, i.e. without energy efficiency measures applied. Subsequently, ΔT is also estimated for the conceptual office building but with applied energy efficiency measures. The ratio between the two corresponds to the percentage of reduction in temperature with respect to the business as usual. Moreover, for consistency with the climate assessments of the other OIs, the formulation of ATR20 and ATR100 will follow the definition in Sausen and Schumann[18].

Generalisation method

The energy consumption of the conceptual office building is scaled by using a proxy calculated as a logarithmic function of the number of aircraft movements. Such a proxy is estimated as the result of a logarithmic fit of the number of employees as a function of the number of aircraft movements for ten airports in Europe. The idea at the basis of the calculation is that the energy consumption is proportional to the number of employees. This fundamental hypothesis needs to be further tested and validated, or adjusted. We plan to engage with the partners in the consortium as well as in the Advisory Board to fine-tune the generalisation method. To facilitate the discussion, the idea is to include the preliminary results presented in D2.3 in the visualisation tool developed by Deep Blue.

Each step of the overall procedure to assess the climate-related KPIs of this OI entails fundamental uncertainties. In the second assessment, we will provide an estimate of the uncertainties of the final KPI value. The uncertainties of our calculations span a wide range of sources, and some of them are not quantifiable. However, we plan to include the error of the fit used to scale the results from one conceptual building to the continental level, the variability linked to the used energy sources, and of the different climate scenarios for the analysis of future conditions.

3.8.3 Assessment process

We will perform a cost-benefit analysis to expand the KPAs in this OI assessment. Considering the type of analysis we performed for the climate-related KPIs, the cost-benefit analysis will be parametric. More precisely, we will calculate the necessary investment to implement the considered energy efficiency measures. The cost calculated for one conceptual building will be scaled, similarly as in the climate assessment analysis, based on the number of aircraft movements. At the same time, we will estimate the savings thanks to the reduction in energy consumption. The energy cost depends on the source, and airports commonly use a combination of energy sources. Therefore, we need to estimate the variability of our results due to different energy scenarios, where with energy scenarios we indicate different combinations of electric and thermal energy to satisfy the total energy demand. In this way, the cost-benefit analysis will include the variability due to the different combinations of energy sources used by airports.

Finally, we will consider qualitative KPIs such as social, market and political acceptance. A passenger survey has already been conducted. The results will be analysed to understand how important it is to passengers how green an airport is. Specific interviews with selected members of the consortium and the Advisory Board and potentially other contacts in the ClimOp wider network will be conducted to evaluate the readiness of the market to accept the initial investment for the energy efficiency measures. Parallel to this, considerations on the political acceptance of such OI will be carried out.

3.9 Comparability of the results

A crucial aspect after investigating OIs in ClimOP is developing mitigation strategies by analysing and ranking the results in work package three. Consequently, a harmonised study of the OIs in WP2 will assist in having a broad feasible combination of OIs when establishing the final mitigation strategies in this project. We have planned to address this criterion as "result comparability," and it is being discussed during the second package. Integration strategies (reported in the section 4) is our first practical step toward comparable results. Within this step, OIs integration opportunities are being investigatedin three categorises of OIs. The subsequent phases for this approach are planned for D2.4.

The comparability of results will only be feasible if all the OIs use the same KPIs and scale. In summary, aiming for this goal requires the results to be compatible with the following factors:

- Time scope
- Geographical scope
- weather condition

Comparing the OIs from different categories may not be achievable as they calculate the KPIs from various perspectives. A more detailed analyse will be carried out in D2.4 to ensure the maximum possible analogy in the montioned factors in all OIs.

4. Integration strategies

The second round of OIs assessment consists of two primary study approaches. Firstly, OI working groups further investigate the individual OIs to cover more KPIs or make the assumptions more realistic, as reported in the previous section. Secondly, integration strategies for each OI category are being analysed to find the synergies and interdependencies among OIs. This section covers requirements and challenges towards integrating OIs in each category.

4.1 Network-related OIs integration

The optimal location of the intermediate stops in a climate-optimal ISO is strongly influenced by the effect of flying lower and the airlines' network. In the same way, the consideration of ISO and flying lower operations influence the optimal network of an airline

The previous modelling iteration has shown that the selected flight altitude impacts the climate response of flights in general and the definition of the climate-optimal ISO in particular. In this context, replacing non-stop missions with ISO generally leads to higher flight altitudes if profiles are optimised towards fuel consumption. This can be explained by the smaller amount of fuel and the resulting lighter aircraft mass, which leads to higher optimal cruise flight levels. Thus, emissions are released at higher altitudes and potentially lead to a higher climate impact. Explicitly reducing flight altitudes of ISO missions could consequently reduce their climate impact. Therefore, a limitation of flight altitudes can additionally increase the climate mitigation potential of climate-optimised ISO (Figure 7). Apart from that, interrupting direct flights with intermediate stops leads to extensions in flight times for landing and take-off, plus potential detours further extending flight times. This does affect not only the cost of the operating airline but also the network in general. Additional speed changes to compensate fuel and CO_2 effects also affect the airlines' operation, which is why this combination's network effects should be assessed in an integrated scenario as displayed in Figure 14.

Figure 14: Connection of LOSL and NETW to ISOC

In the way, the OI of climate-optimised ISO has been modelled, climate impact of different flight levels and ISO missions is already available, for altitudes varying between 29,000 and 39,000 ft. Thus, flying low is implicitly considered in the model workflow. An additional modification of flight speeds currently derived from BADA4 performance data can be modelled additionally within the trajectory calculation process. New calculations of trajectories will have to be performed for speed adjustments in this case, whereas trajectory results and emissions are already available for different flight altitudes. Therefore, an integration of lower flight levels into the evaluation of climate-optimal ISO can easily be performed.

Combining trajectory-related and network-related OIs requires adjustments of the modelling workflow to enable a combination with comparable assumptions. In this context, different approaches can be performed to calculate the trajectory for OI combinations vary regarding effort and accuracy. Combined scenarios, including LOSL, can be calculated in detail by individually simulating every trajectory, ensuring high spatial and temporal resolution. On the one hand, detailed boundary conditions can be considered, such as detailed point profiles of the respective mission and actual wind and weather data from the selected date and time. On this basis, aCCFs can easily be evaluated. On the other hand, high computational efforts are required, and large flight plans need a long time to be simulated. A different approach enables the calculation of a large number of trajectories and resulting emissions aggregated by applying precalculated reduced emission profiles (DLR's RedEmP). For this purpose, a yearly global flight plan can be evaluated under generalised

boundary conditions (e.g. no specific weather conditions but International Standard Atmosphere, ISA, and great circle connections) and fed into AirClim to evaluate its climate response.
Subsequently, a comprehensive look-up table, summarising climate-related and Stakeholder-related KPIs per combination of origin, destination, and ISO airport and selected flight-level is the basis for analysing network effects and generating a solution, combining the trade-offs between climate-optimal and network-optimal solutions.
In contrast to LOSL and ISOC, NETW calculates the network effects of the OI at the airline level. Therefore, the required input will also be at the airline level consisting of airports and OD pairs associated with the representative airline. The implications of implementing ISOC and LOSL in time, cost and ATR of flights for all routes operated by representative airlines are needed to be compiled as a look-up table per selected airline and airline type.
Based on this and the OIs' individual results from D2.3, modelling the combination of the three OIs is suggested as follows:

1. **Flight plan preparation**: Identification of flights (represented by OD pair) that build up the network for three different airlines. One representative airline is chosen per airline type, i.e. KLM for large-size hub-and-spoke, easyJet for low cost carriers and TAP for secondary hub and spoke. For all long-haul routes with a distance of more than 2500 NM, ISO missions are modelled in addition to the direct connections. Two possible ISO airports are considered: the fuel-optimal airport and the climate-optimal one. Furthermore, two different flight levels will be considered (e. g. FL370 and FL310) to incorporate flying lower. The demands per OD pair will be calculated. Furthermore, all aircraft types of the respective airline's fleet will be identified and included in the following simulation.
2. **Modelling climate KPIs, flight time and fuel flow:** DLR's Trajectory Calculation Module (TCM) & GRIDLAB are used to calculate 3D trajectories and emission profiles per OD pair (for direct and ISO mission) for every aircraft type, that is available to the respective airline, and the two selected flight level. Subsequently, climate chemistry model AirClim is used to calculate ATR20 and ATR100 individually per mission. The results are summarized in a comprehensive look-up table containing fuel flow, flight time, ATR20, and ATR100. In the modelling process, the following assumptions are taken:
    - Great circle connections between the airports are assumed.
    - BADA4 aircraft performance data and speed schedule is applied.
    - An average European load factor of 0.84 is considered for all flights.
    - International Standard Atmosphere is used for Trajectory and Emission calculations.
3. **Cost modelling:** Direct operating cost (DOC) will be estimated from flight time and fuel consumption per mission of the look-up table.
4. **Network optimisation:** Based on the data provided in the look-up table, network optimisation is performed. Then the result for each airline type will be calculated by extrapolaiting the result form representative airlines.
5. **Uncertainty modelling:** Following the simulations and evaluations of this integrated scenarios, uncertainties will be evaluated.

The following table summarises the requirements and challenges of this integration strategy.

Table 5: Requirements and challenges of integrated strategy network-related OIs

Requirements	Challenges

• Input required in terms of:
  ○ Given flight plan (OD pair + AC type + frequency) per airline (type)
  ○ Atmospheric boundary conditions
  ○ Flight level
• Boundary conditions to limit computational effort, e.g.
  ○ Limited detour/add. flight time
  ○ Pre-selection of airports
  ○ Great circles
  ○ Average atmosphere data valid for full flight plan considered (ISA)
• Application of AirClim required for a global flight plan, since aCCFs are not validated for a global scenario.
• The following parameter in all OD pairs(available per representative airline) operated by the representative airline in the business-as-usual and after implementing the ISOC+LOSL for all the fleet types (if applicable)
  ○ Flight time
  ○ Direct cost
  ○ ATR20/ATR100
• ATR20/ATR100 uncertainty analysis
	• Combination difficulties might arise due to different boundary conditions compared to LOSL & NETW (ISA vs. individual days)
	• Variety of combinations for flight levels and different ISO options for all routes and fleet types could be computationally intensive requires high computational efforts for scenario simulation
	• Required aircraft performance data may not be available for all the fleet types
	•
	• The changes due to implementing OIs may be smaller than AOMAS resolution and could not be captured
	• Flight-time, passenger acceptance, network effects and capacities at ISO airports might limit the OI's climate-optimal implementation
	•

4.2 Trajectory-related OIs integration

The free routing concept provides an opportunity to fly more efficient routes by removing the fixed air traffic service routes. The concept can be implemented using direct routes in airspace, or a more advanced planning algorithm can be utilised to generate the trajectories according to user-defined objectives. The OI of free routing in high-complexity environment has been implemented according to the first assumption in which the aircraft use shortest paths in free routing airspace. A flight planning algorithm can be integrated with the free routing concept to assess the integrated strategy. The OI of wind/weather-optimised flight planning assumes that there is no route constraint except the initial and final waypoints. Thus, it presents an appropriate implementation of free routing concept with flight planning algorithm. The planning algorithm can generate the optimised routes for free routing airspace when the entry and exit points of airspace are used to assign the boundary conditions in the optimisation problem. In this way, the flight routes in free routing airspace can be chosen by the flight planning algorithm according to the defined objective function. The objective function can be defined as a weighted sum of performance quantities such as reaching the target waypoint, travel duration, fuel consumption, and released emissions. The various components in the objective function and different weights can lead to the different trajectories. However, it is unfeasible to investigate several use cases with different objectives because of high computational cost. We plan to define two different objective functions and assess the planning algorithm with them. The first objective function consists of the travel duration, fuel consumption and a term related to reaching the target waypoint. The second one contains the NOx emission with a relatively high weight in addition to the previous components. We plan to evaluate these OIs together in the second round of assessment to present comparison results for the free routing concept with and without optimised flight planning. The requirements and challenges of integrated strategy for free routing and optimised flight planning are presented in Table 6.

Table 6: Requirements and challenges of integrated strategy trajectory-related OIs

Requirements	Challenges

• Focus on an en-route airspace
• The models used in trajectory simulator and planning algorithm should have same level of fidelity to generate comparable results
• Following data have to be available:
  ○ Flight plans for all aircraft operating in airspace
  ○ Entry and exit points of free routing airspace based on flight plans
  ○ Aircraft performance parameters
  ○ Wind/weather forecasts
•
	• High computational workload to optimise all trajectories for a whole day
	• The optimised flight planning could generate different trajectories depending on the defined objective function. But, it is hard to obtain several case studies because of high computational cost.

4.3 Ground operation-related OI integration

The GHG emissions generated by airport operations are to be attributed partly to the airport operator and in large part to third parties operating on the airport grounds. An additional, indirect source of GHG emissions are passengers and cargo travelling to and from airports.
The operations carried out by the Airport Operator are:

- Plant and civil maintenance and the consequent use of cars and equipment;
- The management of buildings (offices, terminals, etc.) and the consequent consumption of thermal and electrical energy;
- The management of security installations (fire prevention, power supplies, etc.);
- The management of administrative and operational staff;
- The waste and water management;
- Baggage Handling System;
- Winter Operations (de-icing – de-snowing).

The operations carried out by third parties, which have an impact on GHG emissions, are:

- Ground Handling operations;
- Aircraft refuelling operations;
- Maintenance;
- LTO cycles.

A concrete commitment to achieving a low-carbon economy and implementing an ad hoc strategy to combat climate change is no longer just an opportunity for companies but is increasingly becoming a matter of competitiveness. Having always been attentive to environmental issues and actively engaged in reducing its consumptions, SEA Milan has joined the ACI Net Zero 2050 programme, but has set itself an even more challenging objective, namely that of achieving this result by 2030.

In this context, the purpose of the present scenario is to investigate the integrated impact of all ground-related OIs analysed within the ClimOP project, namely the electrification of GSE and operation, the upgrade of the airport infrastructure according to energy efficiency criteria, and the electrification of taxiing operations. Our goal is to quantify the reduction in GHG direct emissions which can be obtained by deploying the three OIs. The research questions to be addressed in the ground-related scenario are:

- What is the cumulative reduction of GHG emissions that can be achieved if all OIs are deployed?
- What is the corresponding climate impact?
- What is the total energy demand in case of full electrification of all ground operations, including taxiing? What fraction of this energy demand can be covered by the energy savings generated by the upgrade of the airport infrastructure? What is the overall investment required to fund this transition towards electrification and energy efficiency?

Because these OIs can in principle be implemented independently, their integration is not expected in principle to encounter specific modelling challenges besides those already discussed in the previous sections. However, to consistently combine the contribution it is necessary to harmonise the modelling methodology adopted for the three OIs and to ensure that the outcomes are consistently calculated. In particular, the models need to output the annual GHG emissions at an airport in the current conditions and after the deployment of the OI. This is possible for the two OIs "Electrification of GSE and operations" and "Upgrade of airport infrastructure", for which it is relatively straightforward to compute integrated fuel and energy consumptions. By contrast, the emissions from taxiing depend on location-specific characteristics of the airport and the operations and it is still under investigation whether it is computationally feasible to calculate the total amount of fossil fuel that is burnt over a year in taxiing operations and the total energy that would be necessary for electric taxiing.
To evaluate the impact of integrating these OIs, we will focus on two case studies:

(a) The ground fleet and taxiing electrification and upgrade of infrastructure at the MXP airport. For this case study, we will exploit the detailed data shared within the ClimOP context by the partners of SEA.
(b) The cumulative impact of ground operations electrification and infrastructure upgrade for at the ECAC level. For this case study, it will be necessary to generalise the results obtained for one individual airport.

Table 7. Requirements and challenges of integrated strategy ground operation-related OIs

Requirements	Challenges

• Model output for business as usual and after implementation of the OIs
  ○ Energy and fuel demand
  ○ Direct GHG emissions
  ○ Direct cost
  ○ ATR20/ATR100
• Possibility to generalise the results to any airport in EU. To achieve this goal, the following elements are necessary:
  ○ Model input: annual number of flight operations at the airport
  ○ Relation to compute the direct GHG emission n from the different sources (taxiing, GSE and operations, office buildings)
	• Generalisation of very specific local characteristics (e.g. the composition of the ground fleet, the size, number and characteristics of the office buildings) require to make fundamental assumptions and simplifications, and consequently introduce significant uncertainties in the results
	• Unavailability of data to validate various components of the models on airports other than SEA MXP and LIN.

5. Conclusion and future work

This deliverable presents the result of the planning for the second round of assessing operational improvements. Inputs from the previous deliverables were required to perform the assessment, and methodology and assumptions were modified and also adjusted to establish a sound study plan for the second round. This document also adds a comprehensive overview of progress status in work package two. The workflows for the second modelling iteration are presented. These results build the basis for evaluating the OIs effectiveness with regards to climate mitigation measures as well as for the analysis of the impact on the different stakeholders in the next deliverables.

As described by the working groups for every OI, further modelling activities can be performed in the second iteration to refine the presented results. The assessment procedures and challenges are described in a separate section dedicated to each OI. To further investigate the synergy among OIs integrated strategies have been taken into consideration. Integration strategies would help generate results with the compound effects of several OIs. We aim to make the results more realistic, and in comparison to individually studying OIs, the integration approach would have a critical role in this direction.

The OIs within each category discussed their requirement and challenges regarding a common integration strategy, and the results are summarised in chapter four. In summary, the current deliverable represents the study roadmaps for the individual and integrated approaches in D2.4.

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