Climate assessment of innovative mitigation strategies towards operational improvements in aviation

D2.2 – Documentation of adaptation of the combined air traffic and climate impact simulation and modelling of operational improvements

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CLIMOP Consortium

CLIMOP Consortium consists of a well-balanced set of partners that cover all the needed competencies and the whole value chain from research to operations. ClimOp Consortium includes representatives from aviation industry (IATA, SEA), academic and research institutes (NLR, DLR,TU-Delft, ITU) and SMEs (DBL, AMIGO).

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Executive summary

This deliverable presents the documentation of the adaptation of the combined air traffic and climate impact simulation and modelling of operational improvements (OI) in ClimOP. The context to the overall ClimOP project is given followed by a description of the methodology being applied to evaluate the different OIs. The methodology is provided for every OI separately as in the course of the Work Package 2 it was decided to parallelize activities in different working groups. During those activities it was made sure that a common reference air traffic scenario including the technological and operational boundary conditions, as documented in D2.1 of ClimOP, is used for conducting the climate impact assessment of the different OIs in order to facilitate a fair and valid intercomparison of the OIs. Hence, for each OI, the respective working group has defined in a number of meetings and discussions the workflow to be created and to be applied to evaluate the performance of the OI. While the focus of WP2 is on estimating the non-CO_2 effects of the OIs, where possible and reasonable, also non-climate related Key Performance Indicators (KPIs) are assessed. In order to allow the reader to quickly get an overview and the essence of the OI model, each OI description section is structured such that first a fact sheet of the OI is presented followed by a more detailed description of the implementation of the workflow on an integrative level including the application and, where required, development or adaptation of involved models. The fact sheets e.g. include information on the scope of the study, the objectives, research gap to be closed, limitations, involved models, and partners. This deliverable also contains a description of the broader stakeholder impact assessment methodology, including details on the cost-benefit assessment approach and social acceptance modelling, which will play a role in some of the OIs. As in the model workflows reference is made to various models and tools of the partners involved, this deliverable also includes overview descriptions of the tools to enable the reader to better understand how the tools interact and how inputs and outputs are interconnected. This deliverable therefore forms an important basis for the numerical experiments which are now being carried out. Initial results of this exercise will be presented in the next deliverable D2.3 together with further information regarding the experiments and potentially necessary adjustments to the methodologies as well as lessons learnt.

Abbreviations

3D	three dimensional
4D	four dimensional
ACACIA	Advancing the Science for Aviation and Climate
aCCF	algorithmic climate change function
ALTERNATE	Assessment on alternative aviation fuels development
ANSI	American National standards
ANSP	air navigation service providers
AOMAS	multi-agent airline operation planning model
ASCII	American Standard Code for Information Interchange
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASK	available seat kilometres
ATAG	Air Transport Action Group
ATC	air traffic controller
ATFM	air traffic flow management
ATM	air traffic management
ATR	Average Temperature Response
ATS	air traffic service
BADA	base of aircraft data
BES	building energy simulation
CBA	cost-benefit analysis
CCF	climate change functions
CMIP 5	Coupled-Model Intercomparison Project 5
CO_2	carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DBL	Deep Blue
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
DOC	direct operating costs
DWD	German Weather Service (Deutscher Wetterdienst)
ECAC	European Civil Aviation Conference
ECMWF	European Centre for Medium-Range Forecast
EEA	European Environment Agency
ECHAM	ECMWF Hamburg
ELEC	electrification of ground equipment of an airport
EMAC	ECHAM5/MESSy Atmospheric Chemistry Climate Model
EPS	expanded polystyrene

ETS	emission trading scheme
EU	European Union
GA	genetic algorithm
GFS	Global Forecast System
GHG	greenhouse gas
GRIDLAB	Global air traffic emission distribution laboratory
GreAT	Greener Air-Traffic Operations
GSE	ground support equipment
H_2O	water vapour
H&S	hub & spoke
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILS	instrument landing system
INEA	Innovation and Networks Executive Agency
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
ISO	intermediate stop operations
ITU	Istanbul Technical University
KPI	key performance indicator
LED	light-emitting diode
LCC	low cost carrier
LTO	Landing and Take-off
NCEP	National Centers for Environmental Prediction
NLR	National Aerospace Laboratory (Nationaal Lucht- en Ruimtevaartlaboratorium)
NM/ nmi	nautical miles
NO_x	nitrogen oxides
OD	origin/destination
OI	operational improvement
QNM	Airport-Centric Queuing Network Model
RCP	Representative Concentration Pathway
R&D	research and development
SEA	Società per azioni esercizi aeroportuali
SESAR	Single European Sky ATM Research Programme
SO_x	sulphur oxides
SO_2	sulphur dioxide
SRES	Special Report on Emissions Scenarios
STD	Schedule time of departure

STA	Schedule time of arrival
T	temperature
TCM	Trajectory Calculation Module
TGT	Trajectory Generation Tool
TMY	test meteorological year
TOM	Trajectory Optimization Model
TOT	Trajectory Optimization Tool
TUD	Delft University of Technology
WGS-84	World Geodetic System 1984
WP	work package

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 2

The overall objective of work package 2 is the iterative quantification of the implications the OIs, which have been selected in the course of work package 1, have on climate change.

For this purpose, an air traffic simulation environment is required, in which the OIs are modelled such that changes in the amount, and the location (including the geographic position and altitude) of the different engine emissions species due to the altered operations become visible with respect to a baseline scenario. Some OIs, such as climate-optimised routing, require the inclusion of weather data and climate change functions (CCFs) in order to assess their climate impact since the OI is directly linked to a weather phenomenon, such as contrail formation regions. For other OIs, such as Intermediate Stop Operations, where the focus is not on specific weather phenomena, their climate impact is adequately estimated using a climate-chemistry response model AirClim. Hence, in a second step, tools (e.g., climate-chemistry response model) and data (e.g., CCFs) are prepared and linked to the air traffic simulation environment. These tools and data are adapted to capture the specific characteristics of the selected OIs appropriately and to capture the climate performance metrics selected in WP1. CO_2 emissions and non-CO_2 effects, such as ozone and methane changes from NO_x-emissions, water vapour changes, contrail-cirrus coverage, and possible impacts from particulates, will be addressed in terms of changes in the concentrations, radiative forcing, and near surface temperature.

1.3 Deliverable 2.2 in the Project's context

The deliverable D2.2 “Documentation of adaptation of the combined air traffic and climate impact simulation and modelling of operational improvement” describes the methodological basis for the climate impact assessment of the selected operational improvements. In the course of work package 1, the OIs have been shortlisted according to a multi-step multi-criteria assessment procedure described in detail in deliverable D1.3 [5]. From the original 25 OIs, 11 OIs were selected with priority, covering four different categories of OIs: Climate-optimised operation of the airline network (five OIs), Climate-optimised trajectories (two OIs), Operational and infrastructural measures on the ground (three OIs), Operational measures at regulatory level (one OI). The selected OIs were then further outlined in deliverable D1.4 with respect to their impact on climate and on the involved stakeholders. The expected advantages/disadvantages of those 11 OIs were also discussed in D1.4. Moreover, a preliminary description of the necessary methodology to study those OI’s impact on climate and the KPIs/methods to evaluate its impact on stakeholders also in terms of feasibility/implementability were given in D1.4 [6].

This deliverable results from the work conducted in Task 2.1, which deals with the preparations of the climate impact assessment of the OIs. For each OI an individual working group was formed comprising of representatives from partners that have a significant interest in the particular OI and can contribute to the modelling and simulation process. These working groups had several in-depth discussions on how to model the respective OI and developed model workflows. As an important first output these working groups derived a harmonized air traffic scenario including assumptions on ground operations, which was comprehensively documented in the deliverable D2.1 [7]. Now, the working groups have finalized their work on the definition of the different numerical experiments to be carried out in WP2. Questions that had to be answered to accomplish this include e.g. “What are the objectives of the individual study on the OI?”, “Which research gap do we attempt to close by this and what is the innovation?” or “What are requirements and limitations of the approach?”. This is documented in chapter 2. The idea, which is also reflected in the substructure of the respective sections, accordingly, is to provide information in a fact sheet-like way to allow the reader to quickly get an overview and the essence of the OI model. These fact sheets also include information on the scope of the study, the involved models, and partners. Furthermore, for each OI an implementation section is given that describes in more detail the model workflow that has been elaborated in the working group and presents the reader an insight into the methodology that will be adopted for the analysis on an integrative level. In chapter 3 also a description of the broader stakeholder impact assessment is given, including details on the cost-benefit assessment approach and social acceptance modelling. Finally, in the annex, the characteristics of the involved tools and models are described.

The findings from WP2 are essential inputs for WP3, where climate impact indicators and stakeholder impact indicators are analysed for the implementation of mitigation strategies.

2. Modelling the climate impact of operational improvements

This chapter documents the results of the effort of the nine working groups devoted to elaborating the details of the experiments to be conducted to analyse the climate impact of the OIs. This deliverable focuses on the methodology description, while the outcomes and findings of the experiments will be presented in the upcoming deliverables. Therefore, in the following, for each OI to be investigated, one section is provided with a fact sheet summarizing the main characteristics of the study and a description of the implementation of the methodology.

2.1 Flying low and slow

2.1.1 Facts

The goal of this OI is to operate the aircraft on lower cruise flight levels with reduced cruise speed (compared to business-as-usual) to shift the location of cruise emissions down. This will lead to a reduction of non-CO_2 climate effects of the flight, as the formation of contrails, but also the impact of NO_x and H_2O emissions can be reduced by this.

- **Objective:** Quantify the potential to reduce the climate impact of Flying low and slow for a specific and harmonized air traffic scenario to enable the comparison with other OIs.
- **Research gap to be closed:** There has been research on Flying Lower and Slower, especially in the context of designing aircraft for different cruise altitudes and speeds. As far as pure operational changes are concerned, in the past, climate impact estimates were obtained by shifting cruise emissions to lower altitudes or considering only one aircraft type. However, no study is known, which demonstrates the potential of the concept by applying a real-world flight plan and point profile data in combination with aircraft performance data for existing aircraft and in a variable atmosphere.
- **Innovations:** The innovations directly are derived from the research gap. For the first time, a weather-based comparison of the climate impact of reference flights as flown today with flights on systematically varied cruise altitudes and speeds based on an existing aircraft fleet in a real-world air traffic scenario and variable weather and future climate impact will be conducted.
- **Requirements**: Pan-European air traffic scenario incorporating detailed flight track and profile data, reproduction of real flight trajectory as a baseline, selected days with characteristic weather, and future average atmospheric conditions to account for climate change.
- **Limitations:** The choice of cruise conditions below the optimum cruise altitude will necessarily lead to increased fuel consumption and, consequently, to additional CO_2 emissions. Although their impact will be overcompensated by the reduced climate impact of the non-CO_2 emissions, this will lead to additional fuel costs, and therefore, Direct Operating Costs plus – as long as only CO_2 is considered in market-based measures (e.g., CORSIA, ETS) – also additional fees. Furthermore, as there are certain altitudes, which will lead to the highest benefits in terms of reducing the climate impact, a concentration of flights in certain altitude bands is expected to occur, causing additional controller workload.

- **Geographic regions:** Europe (ECAC area)
- **Timeline:** selected days in 2018 and for climate-based study average atmosphere for periods 1991-2020, 2021-2050, and 2051-2080

- **Traffic sample:** point profile data for selected days in 2018 from EUROCONTROL R&D archive
- **Models**: TCM (trajectory model, DLR), GRIDLAB (emissions model, DLR), AirClim/aCCFs (algorithmic Climate Change Functions, climate impact model, DLR), Contrail Formation Likelihood model, DOC and ATFM impact will be modelled in a simplified way

2.1.2 Implementation

The study is carried out in two parts: First a weather-based analysis and comparison of the climate impact reduction potential of the OI is conducted. Only pan-European flights are considered, which are obtained in the form of so-called point profiles from EUROCONTROL's R&D archive. For this purpose, firstly a number of characteristic days in months March, June, September, and December (months accessible in R&D archive) 2018 are selected to ensure a sufficient weather variability throughout the study. This selection is done based on classifications from the German Weather Service (DWD) for characteristic weather patterns that occurred in 2018. The most prominent weather situations are identified, and atmospheric data is downloaded from ECMWF. Then, with DLR's Trajectory Calculation Module (TCM), the selected flights are simulated based on BADA aircraft performance models under the prevailing weather conditions to obtain reference trajectories along the point profile routes. Those reference trajectories already include detailed information on the aircraft state, including flight time and fuel flow, in four dimensions. With GRIDLAB, an emission inventory model from DLR, the fuel flow information along the trajectory is translated into emission flows based on fuel flow correlation methods and rasterized into a 3D emission grid. This emission grid is then used to determine the climate impact of the reference flight with the climate response model AirClim or algorithmic Climate Change Functions (aCCFs). Block fuel and time information will also be processed in a cost model to calculate the operating costs. From those, KPIs related to passenger acceptance can be derived (e.g., in a qualitative way), but this will be dealt with at a later stage in the work package. Also, the influence on the controller workload shall be estimated in a rather qualitative way (involving experts from IATA) by analysing the changes in the traffic scene and calculating proxy values such as, e.g., number of aircraft movements per airspace volume per time. Finally, also the contrail formation likelihood shall be determined by predicting areas, in which the contrail formation properties (Schmidt-Appleman criterion plus ice-supersaturation) are fulfilled, and by calculating the distance, the aircraft are is travelling through these regions (potential contrail distance).This evaluation workflow will then also be executed for trajectories that result from shifting the cruise altitude of the original (reference) flights to lower altitudes and adapt the cruise speed accordingly. As a result, for the different cruise conditions, the benefits in terms of reduced climate impact can be compared with the costs, both monetary costs and increased emissions.

The second part of the study is a climate-based analysis. Here, average atmospheric conditions over a period of 30 years are used for the periods 1991-2020, 2021-2050, and 2051-2080. The atmospheric data are obtained from the CMIP5 database as multi-model ensemble mean for the Representative Concentration Pathway RCP4.5, which is available to AmigoClimate. The same flights as in the weather-based analysis will then be simulated under those different climatic conditions to study the impact of a changing climate on the potential of flying lower and slower.

Flying Low and Slow

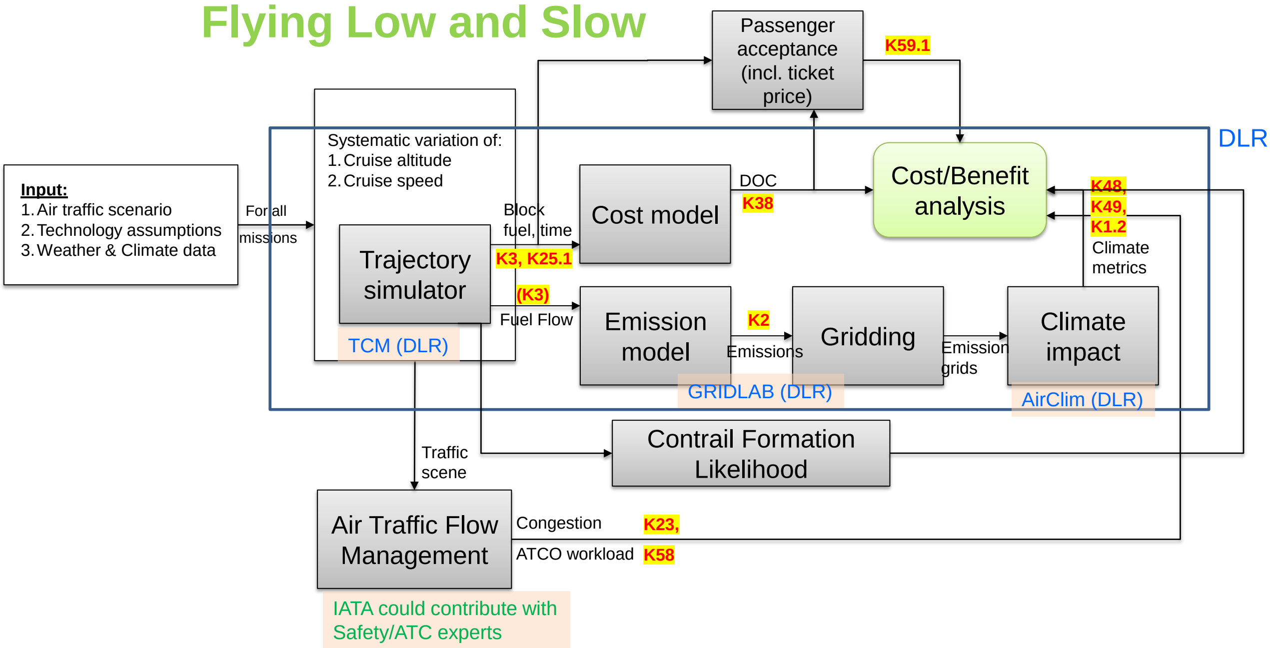

Figure 1: Workflow scheme of modelling the OI of Flying Low and Slow (highlighted identifiers refer to KPI definition according to ClimOP deliverable D1.3 [5])

2.2 Free routing in high-complexity environment/flexible waypoints

2.2.1 Facts

This OI aims to examine the impact of removing the fixed air traffic service (ATS) routes in high-complexity airspaces.

- **Objective:** Our objective is to present an appropriate implementation of this concept for high-density airspaces and analyse its impact on the climate and different stakeholders.
- **Research gap to be closed:** The current literature mainly focuses on low- and mid-density airspaces to implement the free routing concept, whereas this study will focus on high-density airspaces to expose the impact of this concept for high-complexity workspaces. Besides, this study will evaluate the concept from the perspectives of different stakeholders and the environment contrary to the previous studies.
- **Innovations:** Implementation for high-density airspaces and evaluation of the concept from perspectives of different stakeholders and the environment.
- **Requirements**: Flight plans of aircraft that will operate on the analysed airspace, aircraft performance parameters, assumption of international standard atmosphere ISA).
- **Limitations:** In the implementation of free route airspace, the aircraft will use direct routes. This assumption could limit the efficiency of the operation.

- **Geographic regions:** ECAC area
- **Timeline:** 1 day (2018)
- **Traffic sample:** point profile data from ALLFT+, sample filtered by the boundaries of the analysed airspace, fixed aircraft type.

- **Models:** Trajectory Generation Tool (TGT, based on BADA4, ITU), Emission model and gridding (ITU), aCCFs (DLR), DOC and ATC workload will be modelled in a simplified way (ITU)
- **Contributing partners:** ITU, DLR

2.2.2 Implementation

For the implementation of the free routing concept, the case study will focus on a high-density en-route airspace [8] in the ECAC area. The flight plans of the air traffic will be obtained from ALL_FT+ data [9] in which a set of waypoints and departure time are presented to indicate the flight plan and the flown route of an aircraft. For the application, the trajectory generation tool will simulate the traffic in the corresponding airspace in which aircrafts fly according to their flight plans. The trajectory simulator contains an aircraft performance model and trajectory tracking algorithms. While the aircraft performance model is a set of non-linear differential equations that are used to drive the aircraft dynamics, the trajectory tracking algorithms are used to generate the required control inputs to follow a reference trajectory. The model parameters are obtained from BADA4 (Base of Aircraft Data). In the trajectory simulation module, two different scenarios will be performed to analyse the free routing concept. Firstly, a base scenario will be produced using the real flight plans. In this scenario, the aircraft will fly according to their original flight plans by obeying the ATS routes. In the second scenario, the flight plans will be modified using direct routes between entry and exit points of the airspace. In this way, the ATS routes will be removed, and the aircraft will utilize the direct routes/shortest paths to implement the free routing concept. The simulation results of both scenarios will be generated by the trajectory simulator. Then, the impact of the OI on different stakeholders and the environment will be assessed using the obtained trajectories in both scenarios. The travel duration will be directly used as an indicator of passenger acceptance. The impact of the OI on the airlines will be assessed using the fuel flow/fuel cost, on-time performance, and routing efficiency. The ATC workload will be used to evaluate the impact of the concept on the air traffic controllers. It will be estimated using the average number of sector entries, vertical movements, and potential interactions. Lastly, the released emissions will be calculated using the emission model, which uses the fuel flow as the input. The impact of the concept on the environment will be assessed using the released emissions. Then, after gridding of the emissions, the climate metrics will be calculated via aCCFs (algorithmic climate change functions) to analyse the impact of the concept on the climate.

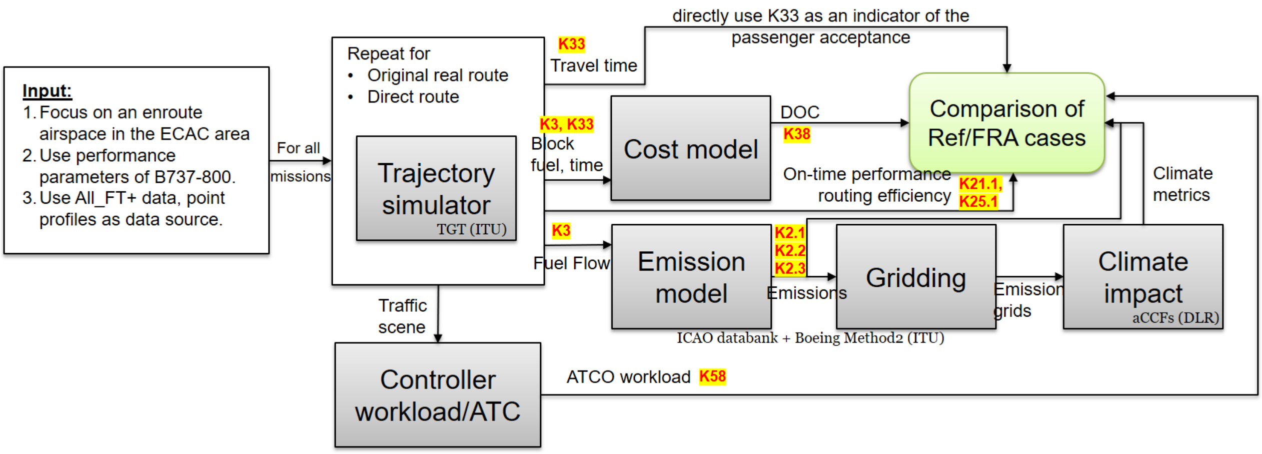

Figure 2: Workflow scheme of modelling the OI of Free Routing in High-Complexity Environment (highlighted identifiers refer to KPI definition according to ClimOP deliverable D1.3 [5])

2.3 Climate-optimised flight planning

2.3.1 Facts

This OI aims to identify the mitigation potential of aviation overall climate impact (CO_2 and non-CO_2) by identifying climate-optimized aircraft trajectories.

- **Objective:** Our objective is to identify alternative trajectories, which avoid regions in the atmosphere which are strongly sensitive to aviation emissions with regards to climate impact.
- **Research gap to be closed:** The concept of climate-optimized trajectories needs to evaluate to what extent alternative trajectories are possible, which benefits but also and which costs and trade-offs occur**.**
- **Innovations:** The overall approach will be applied to specific weather situations which are expected to have a large mitigation potential due to the synoptical situation. For the first time, such a pre-selection of promising weather conditions is envisaged, focussing on climate impact of nitrogen oxides (effects on ozone production and methane depletion), water vapour, and contrail cirrus.
- **Requirements**: For the selected weather situation, comprehensive (spatially and temporally resolved) information on the climate impact of aviation emissions (at a given location) is required. Provision of such data requires an analysis of the associated uncertainties and how to consider them adequately in the overall performance assessment.
- **Limitations:** Current state of knowledge does not yet provide final climate change functions, but only prototypes are available.

- **Geographic regions:** Europe (ECAC region)
- **Timeline:** the year 2018
- **Traffic sample:** Selected days in 2018
- **Models**: TOM (trajectory optimization model, partner DLR), ACCF (climate impact model, partner DLR)
- **Contributing partners:** DLR, ITU, TUD-ANCE, IATA

2.3.2 Implementation

The modelling chain on climate optimized flight planning relies on the provision of spatially and temporally resolved information on the sensitivity of the atmosphere to aviation emissions. Considering this climate impact information in the overall objective of the trajectory optimisation allows us to evaluate and identify alternative trajectories which have a lower climate impact. Associated with this lower climate impact, the overall performance of these alternative trajectories is quantified, and used in an overall analysis, resulting in Pareto-Solutions. In the first step, aCCFs from weather data are calculated, which provide climate impact information to ATM. In the Trajectory simulator, the original real route and the optimized flight are calculated, while applying the multi-criteria objective function (adopting varying weights). From the fuel, flow the emissions can be calculated with the emission model, gridding of data, provides the spatially and temporal information which is required for calculating the climate impact relying on aCCFs.

Climate-optimized flight planning

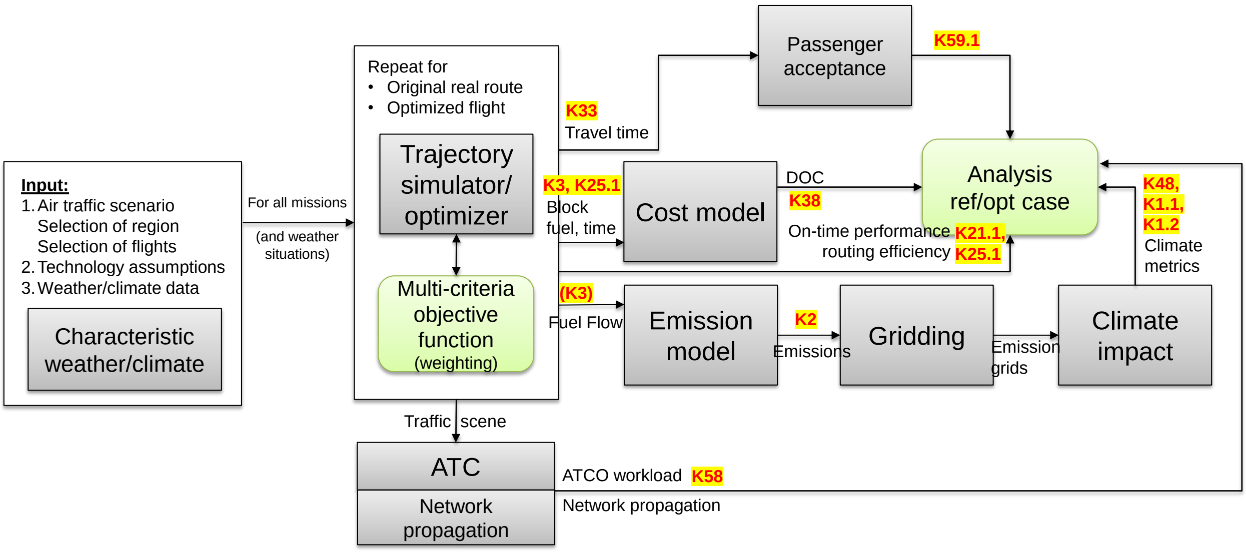

Figure 3: Workflow scheme of modelling the OI of Climate-optimised flight planning

2.4 Wind/weather-optimal dynamical flight planning

2.4.1 Facts

This OI aims to optimize flight trajectory by considering the available wind/weather information to minimize the negative impact of wind/weather on the operation.

- **Objective:** To reduce flight duration, fuel consumption, and released emissions by optimizing the trajectory to benefit from using wind/weather information.
- **Research gap to be closed:** Analyse the impact of the concept on different stakeholders and the environment.
- **Innovations:** Evaluation of the concept from perspectives of different stakeholders and the environment.
- **Requirements**: Original flight plans of aircraft, aircraft performance parameters, wind/weather information.
- **Limitations:** It may not be possible to obtain the global optimum in realistic implementations because of non-linearities in aircraft dynamics. The discretization can also lead to a local minimum solution. Therefore, the planning algorithm can generate a sub-optimal solution.
  Dynamical flight planning will be performed in a tactical time scale based on a wind/weather forecast fixed for a six-hour period.

- **Geographic regions:** North Atlantic Corridor, or ECAC area
- **Timeline:** 1 day (2018)
- **Traffic sample:** point profile data from ALLFT+, traffic sample filtered by the boundaries of the corresponding airspaces
- **Models:** Trajectory optimization (ITU), Emission model and gridding (ITU), aCCFs (climate impact model, DLR), DOC and ATC workload will be modelled in a simplified way (ITU)
- **Contributing partners:** ITU, DLR

2.4.2 Implementation

The focus of the wind/weather-optimized flight planning concept will be on en-route airspaces. The real flight data will be used to simulate the traffic. The flight plans of the air traffic will be obtained from ALL_FT+ data [9]. The wind/weather information will be obtained from the NCEP GFS (National Centers for Environmental Prediction – Global Forecast System) data. A day with a moderate/severe wind phenomenon in the corresponding area will be chosen to implement the OI. For the application, a trajectory optimization module will be used. In this module, the planning problem will be transformed into an optimization problem to generate the optimized strategies with regard to defined objectives. An aircraft performance model, performance limits, and other restrictions will also be utilized to consider the dynamical constraints. The trajectory optimization module will generate the optimized trajectories. By comparing the optimized trajectories with the nominal trajectories, the impact of the concept on different stakeholders and the environment will be assessed. Passenger acceptance will be evaluated using the travel durations. For evaluation of the concept from the perspective, the fuel consumption/fuel cost, on-time performance, and routing efficiency will be utilized. The ATC workload will be considered as an indicator of the effect of this OI on the air traffic controllers. It will be estimated using the average number of sector entries, vertical movements, and potential interactions. Finally, the released emissions will be calculated based on the fuel consumption via the emission model, and the impact of the concept on the environment will be assessed using the released emissions. Then, after gridding of the emissions, the climate metrics will be calculated via aCCFs (algorithmic climate change functions) to analyse the impact of the concept on the climate.

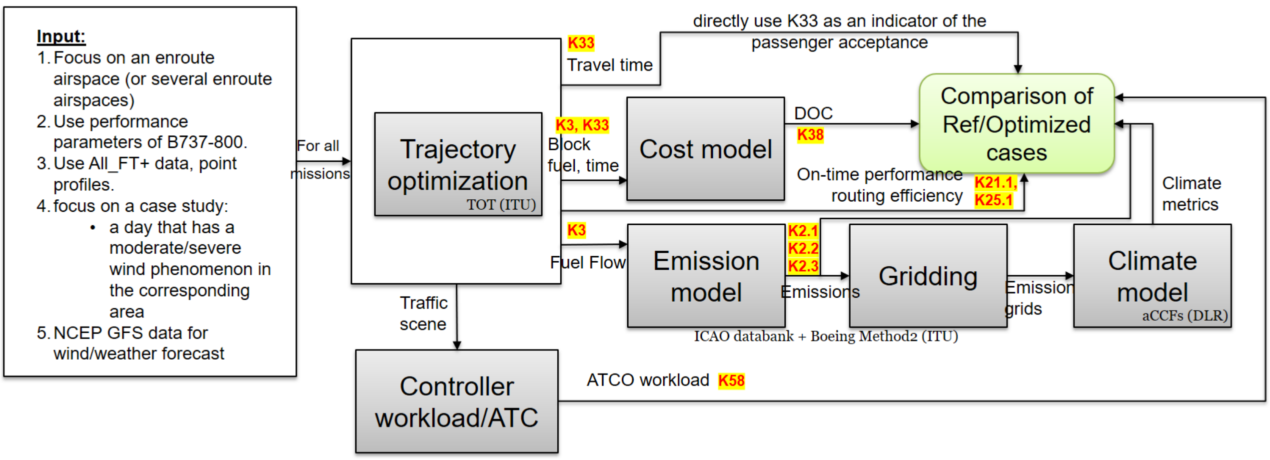

Figure 4: Workflow scheme of modelling the OI of Wind/Weather-optimised Flight Planning

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

2.5.1 Facts

In this OI, the implication is being investigated of taking into account environmental effects of flights when planning operations at airline level. In particular, planning the network structure would help airlines reduce their climate impact by minimising their profit loss.

- **Objective:** Reducing the climate impact of airline operations through optimising the network structure, assuming airline's minimum target values in terms of ATR reduction and operations profitability.
- **Research gap to be closed:** Network planning is a strategic decision in airline management and is primarily studied to increase the airline's profitability. In this

research, we are aiming to incorporate climate effects associated with route development decisions and re-plan the airline network to reduce ATR. Furthermore, the next steps could be considered to find a tailor-made trade-off associated between the operational profit and ATR contribution when operating a network based on different airline business models.

- **Innovations:** For the first time, we consider the climate impact of flights at the strategic level. We introduce climate impact goals to the commonly used monetary objectives when solving the network planning problem commonly used in literature [10]. Furthermore, we will model climate impacts at airline level.
- **Requirements**: Itineraries demand within the study scope, airfare of itineraries, airline fleet information, ATR values associated with specific flight legs within the study scope.
- **Limitations:**
  - Network planning requires suitable infrastructure and slot coordination adjustment at the different airports within the study scope. Given the complexity of modelling these factors, these will be neglected.
  - The ATR value is susceptible to the weather conditions of the flight. To enable flight planning in each quarter, average climatological values are assumed per quarter.
  - The operational cost consists of many components, which may vary among airlines and regional situations. An average operational cost for each aircraft type is assumed in this study.

- **Geographic regions:** flights from/to/within the ECAC area
- **Timeline:** 1 year (2018)
- **Traffic sample:** Annual aggregated flight schedule data from Sabre Market intelligence database (01/01/2018 – 31/12/2018). Traffic sample filtered by airlines and itineraries, which have origin or destination airport within the ECAC area. Data is aggregated per quarter of 2018.
- **Models**: AirClim (climate impact model, DLR), AirTraf (trajectory climate impact model, TUD-ANCE), AOMAS (multi-agent airline operation planning model, TUD-ATO)
- **Contributing partners:** TUD, DLR

2.5.2 Implementation

The implementation of this OI relies on an off-line pre-processing of demand data and pre-calculating the ATR of Origin-Destination (OD) pairs, where at least one of them is within the ECAC area.

Planning a network to be operated by an airline is mainly driven by the estimated demand between the considered OD pairs. Data extracted by DLR from the Sabre Market Intelligence database [11] will be used to obtain the historical passenger demand for itineraries. This database contains the airfare of flights, including the airline which operated that flight. In the pre-processing step, a total demand, including its average airfare and airline type for all aiming itineraries, will be extracted quarterly for 2018.

On the other hand, flying between each OD pair will produce a specific ATR depending on the weather conditions, flight trajectory, and aircraft type. EMAC/AirTraf model [12] will be used to calculate the cost-optimal and ATR-optimal trajectories for OD pairs and create a set of ATR values associated with different aircraft types that could operate the route. The ATR value will be calculated based on a representative input condition (demand and average weather condition) according to the four quarters of 2018. A more detailed explanation of the process followed in the AirTraf is depicted in Figure 5 (Climate box).

Given the inputs mentioned above, the AOMAS model will optimise a network for three representative airline types (major hub-and-spoke (legacy), secondary hub-and-spoke, and low-cost-carrier). Based on the type of airline and its business model, a point-to-point, a hub-and-spoke network or a mix of both topologies will be assumed. AOMAS model relies on a dynamic programming approach to find each representative airline's most profitable flight schedule. The flight schedule will include an operational timetable which indicates all served routes and aircraft type used. So that the total ATR could be calculated by summing up the ATR associated with each route. To extrapolate the result to include all airlines operating within the study scope, we will scale up the amount of profit loss vs. ATR reduction per airline type. The scaling will be conducted proportional to the number of aircrafts for each airline or an estimation of their revenue-passenger kilometres per year. The total potential reduction in ATR will be obtained after adding results for each airline type.

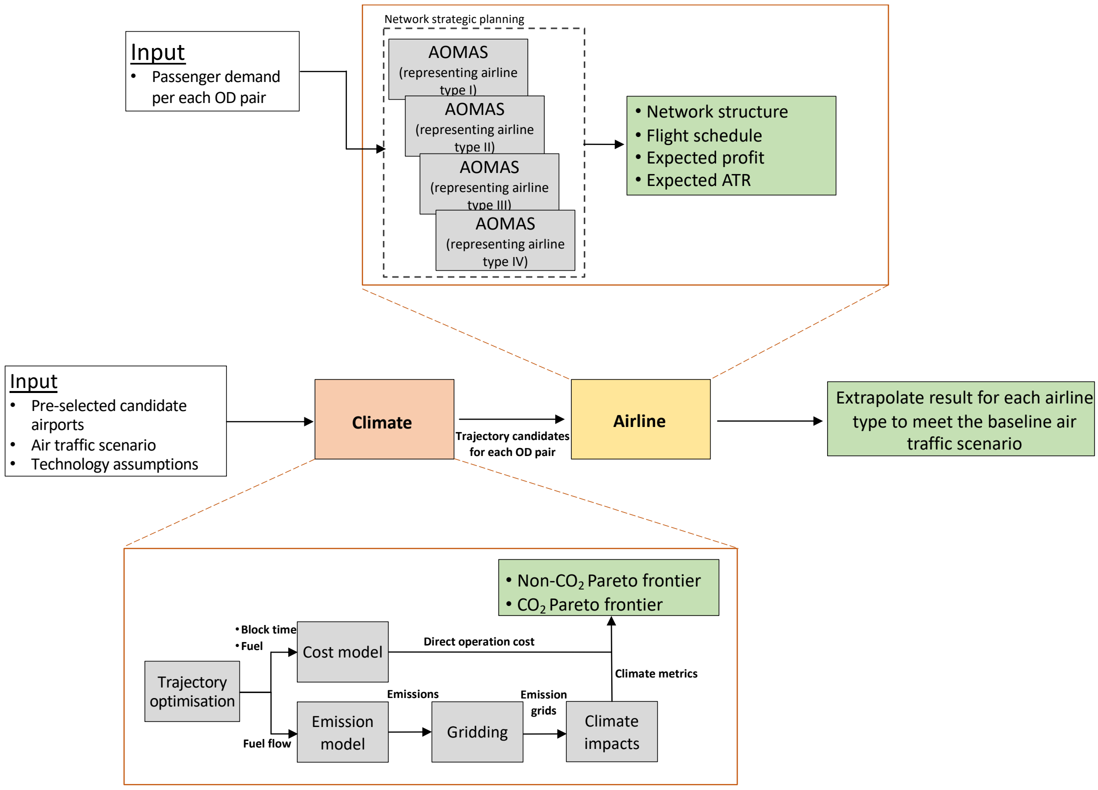

Figure 5: Workflow scheme of modelling the OI of Strategic planning: merge/separate flights; optimal hub-spokes/point-to-point operations

2.6 Climate-optimised intermediate stop-over

2.6.1 Facts

The goal of this OI is to replace nonstop long-haul flights with heavy aircrafts and a full tank by two or even more sub-missions with reduced tank content to save weight of carried fuel and thus reduce fuel consumption.

- **Objective:** Reduction of CO_2 and non-CO_2 effects by interrupting a long-haul flight mission at an intermediate stop airport for refuelling

- **Innovations:** Unlike previous Intermediate Stop Operations (ISO) studies, both the choice of the intermediate stop airport and the cruise altitude is made climate-optimal instead of fuel-optimal
- **Research gap to be closed:** ISO is a well-investigated concept to reduce CO_2 emissions by enhanced fuel efficiency. But it is still unknown if also non-CO_2 effects, e.g., contrail formation, can be reduced by shorter legs and an intermediate stop for refuelling. The selection of the intermediate stop airport will be performed with regards to climate impact, while it has previously been selected based on fuel efficiency. In a second step, state-of-the-art aircraft can be redesigned for shorter ranges, leading to further saving potential.
- **Requirements**: Traffic scenario should be on a global scale, detailed flight track data is not necessary, assumption of great circle routes is sufficient, climatological mean values of atmospheric conditions are considered.
- **Limitations:** The application of climate optimised ISO could overload the capacities of potential ISO airports that are relatively small and may need to be extended. Potential climate-optimal airports have to be preselected to limit the number of calculations to be performed. Thus not all possible combinations can be evaluated. The applied airport base has no detailed information on the prevailing runway conditions and ILS equipment, so non-suitable airports might be selected for the investigation.

- **Geographic regions:** worldwide medium/long-haul flights from or to ECAC area
- **Timeline:** 1 year (2018)
- **Traffic sample:** annual aggregated flight schedule data from Sabre Market intelligence database (01/01/2018 – 31/12/2018), sample filtered by wide-body sub fleet, origin or destination airport within the ECAC area and great circle distance between origin and destination > 2500NM
- **Models**: Trajectory Calculation Module (TCM, trajectory model using BADA4 flight performance data, DLR), GRIDLAB (emission modelling and 3D gridding, DLR) AirClim (climate impact model, DLR), DOC will be modelled in a simplified way
- **Contributing partners:** DLR, TUD-ATO

2.6.2 Implementation

Based on an annual flight schedule scenario for 2018 extracted from Sabre Market Intelligence database, during a pre-processing step, only flights whose origin or destination airport is located within the ECAC area and with a great circle distance above 2500 nautical miles (NM) will be selected. From those remaining long-haul missions, only long-haul aircraft types that can be modelled with BADA4 performance models will be further considered (i.e. A330, A340, A350, A380, B747, B767, B777, B787), so that approximately 15% of the year's worldwide available seat kilometres (ASK) are still covered. Identical scheduled missions are aggregated over the year.

In a preselection process, appropriate intermediate stop airports are selected along the great circle routes based on the corresponding detour and their eccentricity from the fuel-optimal position between origin and destination. To increase performance, only representative airports are selected if many ISO options are geographically close to each other. The next step is modelling all trajectories of the sample with the Trajectory Calculation Module (TCM). For each direct OD connection and all selected ISO missions, cruise altitude is varied, and every trajectory is saved individually. The emissions along the trajectory will be converted to a numerical grid with GRIDLAB tool. Based on the spatial emission distribution, the climate metrics are calculated with the DLR climate response model AirClim to assess the climate impact for all considered missions and each combination of ISO airport and cruise altitude. On this basis, the climate-optimal combination of

ISO airport and cruise altitude is selected for every mission. After an aggregation on a global scale, the final results allow a comparison between the reference scenario of nonstop operations and the ISO case. Additionally, a third scenario where aircrafts, designed for a shorter range, replace the long-haul fleet can be calculated and considered. As the application of ISO may enhance the fuel consumption, and lead to congestion at some of the most popular ISO airports and disturb the integrity of the global network. The network effects and the direct operating costs (DOC) of all investigated OD missions will be verified and quantified with simplified methods by TUD.

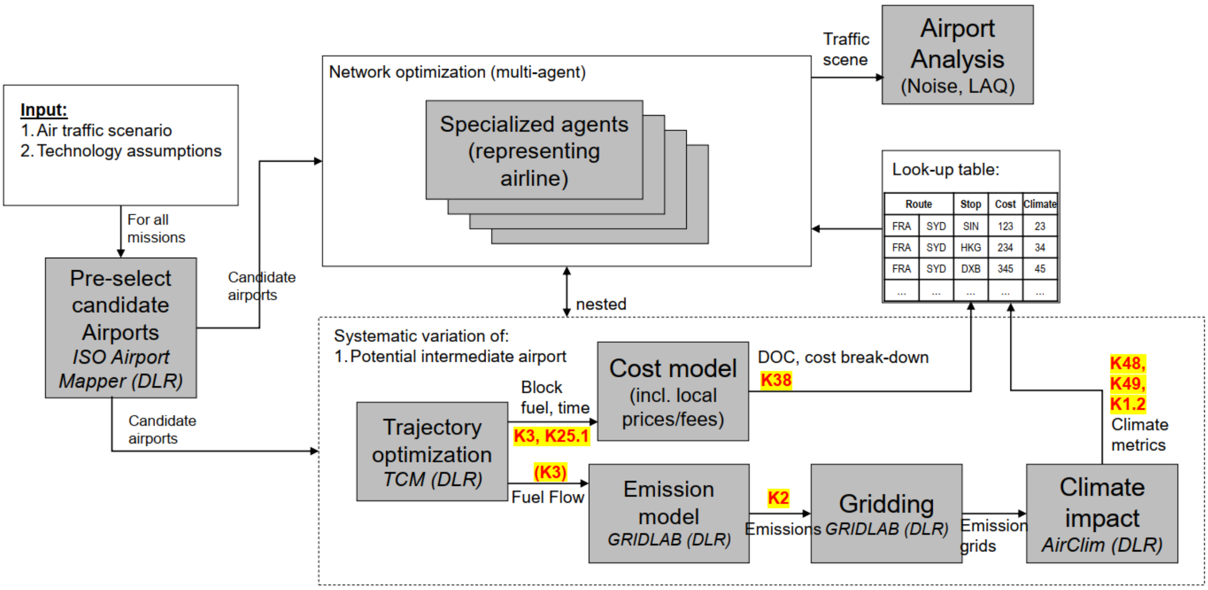

Figure 6: Workflow scheme of modelling the OI of Climate optimised Intermediate Stop Operations

2.7 Single engine taxiing / E-taxi and hybrid

2.7.1 Facts

The goal of this OI is to significantly reduce the combustion emission of fuel in aircraft engines by reducing their use on the ground. Ground movement is then either achieved by the other engine, an on-board electric motor or a tow truck.

- **Objective:** Determine the potential savings in fuel and emissions per aircraft and/or towing vehicle for different airports.
- **Research gap to be closed:** Combining various data sources, including aircraft, airport and flight schedule data, using algorithms that can calculate the average and marginal fuel consumption and applying these methods for existing and future scenarios.
- **Innovations:** Not only the benefit of existing solutions is evaluated, but also the potential benefits for new ones, such as various sizes of towing vehicles and on-board electric motor-based systems are investigated. Also, an analysis is made for a mixed solution: A tow truck at the nose wheel providing electric power to the electric wheels on the main gear of the aircraft. For battery powered towing, also a time allowance for charging will be analysed.
- **Requirements**: A traffic schedule per airport for towing and a schedule per airline for e-taxiing, fuel consumption and emissions per time unit during taxi for all aircraft types, Costs estimations for possible towing and e-taxi solutions

- **Limitations:** The main uncertainty is that towing vehicles returning from the runway could cause congestion on single direction taxiways. Solving this, by adapting service roads, is outside of the current scope.

- **Geographic regions:** Europe, large airports (e.g. AMS, MXP)
- **Timeline:** longer period of time
- **Traffic sample:** 4 days flight schedule data
- **Models**: Mixed integer linear programming model for assigning tow trucks to flights (similar to the flight to gate assignment model) and assignment model to assign e-taxi equipped aircraft to flights within an airline network
- **Contributing partners:** TUD, SEA, Aeon project

2.7.2 Implementation

For all methods, the common first step is to determine the potential savings in fuel consumption and emissions per aircraft ground movement for all flights in the scenario, based on the (average) taxi time or distance. This is illustrated in Figure 7.

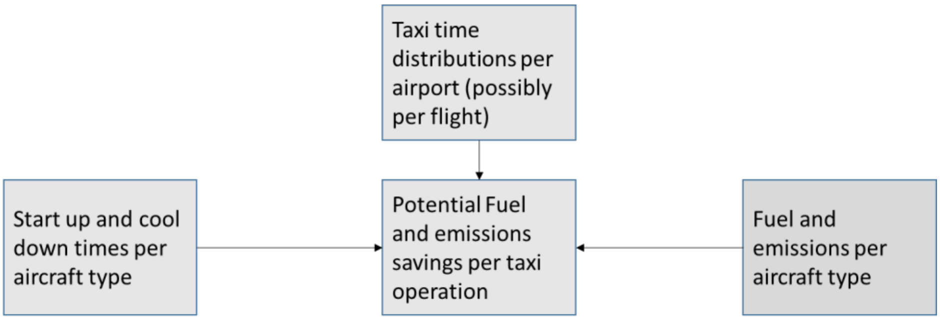

Figure 7: Savings per aircraft ground operation

For towing either a pre-determined type and the number of towing vehicles are assigned to all compatible flights at the airport, and the total fuel consumption is then minimized. Increasing the number of vehicles by one then results in marginal fuel saving per vehicle, illustrated in Figure 8. Optionally, fuel costs are introduced together with a fixed cost per towing vehicle to determine the optimum number of towing vehicles for multiple airports for the overall market size.

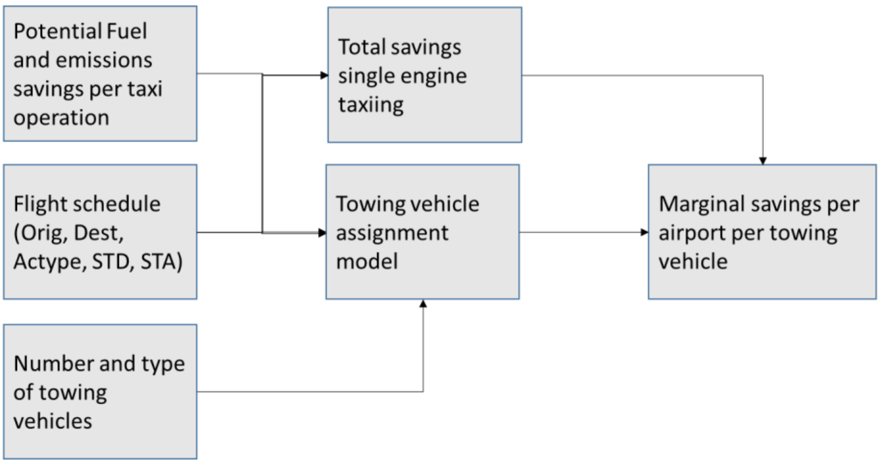

Figure 8: Determining marginal savings per towing vehicle

For e-taxi, a similar strategy is applied, as shown in Figure 9. Here a number of aircraft with and without e-taxi are set. These are the assigned to an overall flight schedule in such a way so that overall fuel consumption is minimized, taking into account the extra fuel burn during the flight due to the added weight of the e-taxi system.

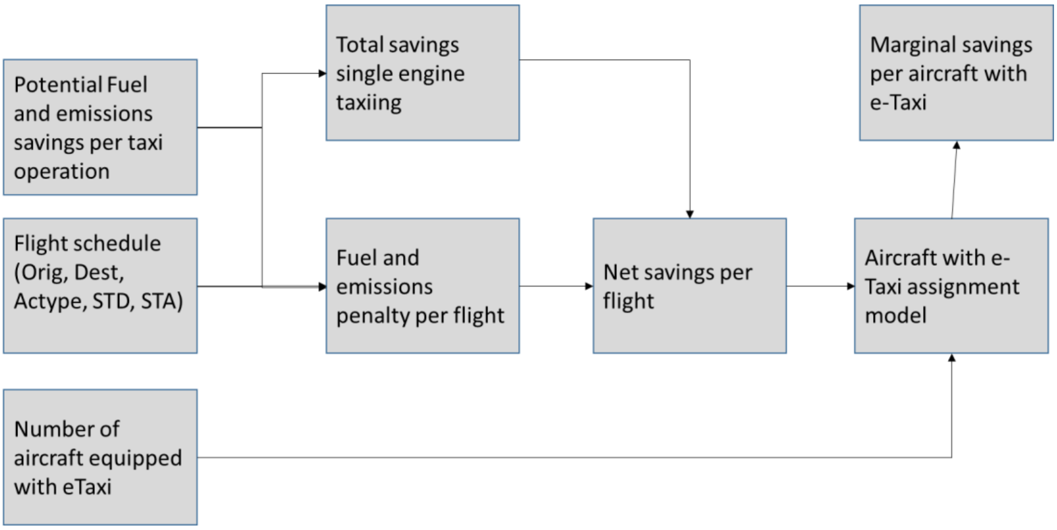

Figure 9: Determining marginal savings per e-taxi equipped aircraft

Finally, a hybrid solution will utilize a combination of both models.

2.8 Electrification of ground vehicles and operations

2.8.1 Facts

The goal of this OI is to replace the current, fossil-fuel-based fleet of ground vehicles at the airports with electric analogues to reduce the emissions of ground operations.

- **Objective:** Reduction of CO_2 and non-CO_2 emissions at airport level
- **Research gap to be closed:** It is broadly accepted that the electrification of ground support equipment will help airports reach the goal of net zero carbon emissions. The net variation of CO_2 and non-CO_2 emissions resulting from this electrification has yet to be computed, as well as the impact this variation has on climate in terms of radiative forcing and temperature response. ClimOP will fill this gap.
- **Innovations:** The ClimOP project will, for the first time, calculate an estimate of how much Greenhouse Gas (GHG) emissions can be cut by electrifying the ground fleet of an airport and what impact this reduction has in terms of climate change mitigation.
- **Requirements**: Number and average yearly use of ground vehicles at a given airport. Alternatively, as a proxy for its size and thus for the size of its ground fleet, the average number of flight operations at that airport.
- **Limitations:** The SEA fleet used for reference is simplified into three vehicle categories based on size (small, medium and large vehicles). The fuel consumption and emission data within each category are also averaged for scaling purposes. The synthetic fleet is created using reference data based on SEA's current fleet.

The simplified fleet, average use and consumption, average emissions, and average climate impact calculations limit the accuracy of the model predictions.

- **Timeline:** 1 year (2019)
- **Data sample:** Ground fleet data of Linate and Malpensa airports in the year 2019 and number of flight operations in the same period and locations.
- **Models**: Diesel, petrol and electric car consumption and emissions [13], [14],[15]. Average GHG emissions from electricity generation [16]. Average temperature response and radiative forcing of given GHG emissions from road traffic [17].
- **Contributing partners:** SEA, DBL

2.8.2 Implementation

The purpose of the model to be implemented is to estimate how many greenhouse gases are emitted in airport ground operations with current ground support equipment (GSE) and to show how this compares to the emissions of a theoretical all-electric fleet. Together with a cost-benefit analysis, the tool serves as a guide for the eventual electrification of ground operations. In practice, the model to be implemented is built to receive in input a set of data about the ground fleet at the given airport. This data includes: the number of ground vehicles, the vehicle category (e.g., personnel car, bus, refuelling truck, etc.), fuel used, and average yearly distance covered. This data can be directly fed to the model being developed, or it can be extrapolated (according to some assumptions described in Section 4.5) using the average yearly number of flight operations at that airport as a proxy for its size and, consequently, for the number and type of its ground vehicles. The model outputs the estimated average fuel consumption of the airport ground fleet and the corresponding GHG emissions. In addition, the model computes the energy demand of a synthetic fully-electric fleet to replace the current one, the amount of GHG emitted in generating this energy, and the estimated costs for the transition from fossil-fuel to electric vehicles.

The process to implement the model is described as follows.

1. The input file of all ground-operations vehicles is read into an ad-hoc Python script.
2. The entire vehicle set is then divided into small, medium, and largely based on their model types.
3. Two reference tables are created: One table contains the average fuel consumption per vehicle size and fuel type, and another contains the average GHG emissions per vehicle size and fuel type.
4. For each size category, the number of vehicles and the number of yearly kilometres are counted. The vehicles from each of the three size categories are then cross referenced with the consumption data to obtain an annual fuel consumption value as well as a yearly GHG emissions value.
5. The synthetic fleet is then created using equivalent electric vehicles as replacements for current vehicle models found at SEA airports. In most cases the model has a direct alternative electric model. If this is not the case, a similarly sized and purposed model is used. Data about power consumption was collected for the new electric vehicles [13][14]. Their range, capacity, and use provide a value for the yearly electrical energy required to power the electric fleet.
6. While electric vehicles have negligible GHG emissions, electric energy is typically generated in power plants that use a variety of sources, most often coal, petrol, and gas [18]. The model uses literature results [16] to calculate the GHG emission corresponding to the generation of an amount of electrical energy equal to the

energy demand of the electric fleet computed at the previous step. The emissions are also broken down into the gases that compose them such as CO_2, SO_2, NO_X, and CO, for a more detailed emissions estimate (see Table 2 in Section 4.5).

7. The tool then calculates a percentage denoting how much of last year's total global GHGs it is responsible for, using its current fleet. The same calculation is performed with the reduced emissions from the synthetic fleet.
8. These two percentages are used to calculate a percentage reduction in global greenhouse gas emissions, due to the electrification of the ground operations fleet. Using recent values for global change in radiative forcing based on GHG emissions [17], the reduction in emissions corresponds to a reduction in radiative forcing, which is then used to calculate the change in average global temperature.
9. The model also estimates the costs and benefits associated with replacing the current, fossil-fuel-based vehicles with a fully-electric fleet. The variables that are taken into account are purchase and maintenance costs of the current and new vehicles, and the costs of fuel and electric energy. The model will enable the user to decide the time span for the transition of the fleet. Therefore, literature projections of the evolution of vehicles and fuels prices over the next decade are used, and possible incentives and disincentives that National and EU regulators put, or will likely put, in place to foster this transition. The cost-benefit analysis also indirectly accounts for the change in reputation of the airport among passengers and citizens as a result of the commitment to reduce the emissions. The effect of the social acceptance is estimated by the mean of a passenger survey described in Sect. 3.2.
10. All the information computed by the model is stored and sent to an ad-hoc visual component for displaying to the user. The outputs are estimated values which help the user identify the emissions for their current fleet, energy requirements and emissions savings for their future fleet, and financial information for guiding the transition. All outputs are shown in Table 1 in Sect. 4.5.

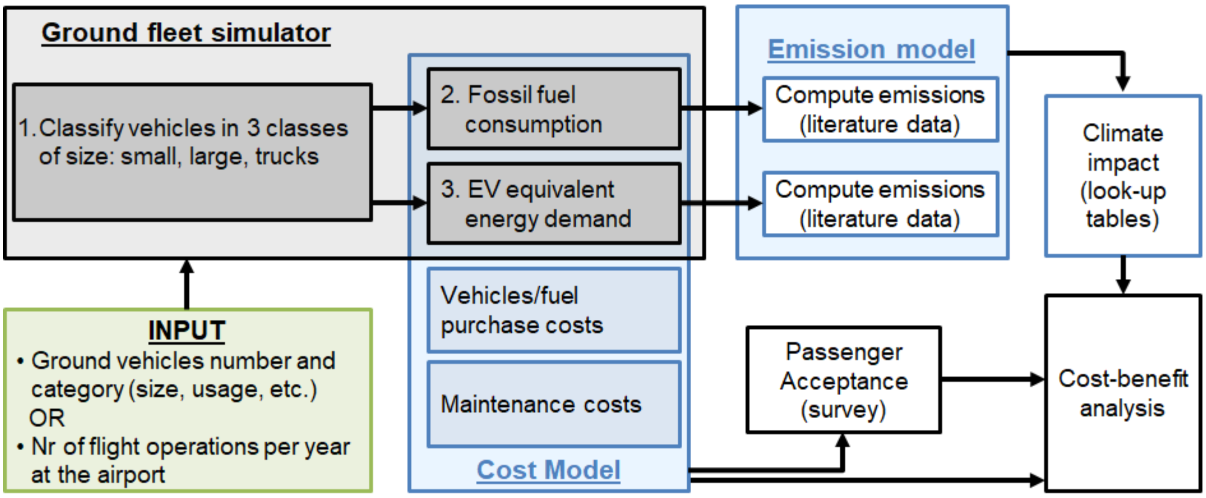

Figure 10: Workflow scheme of modelling the OI of "Electrification of ground vehicles and operations"

2.9 Upgrade of the airport infrastructure according to energy efficient criteria

2.9.1 Facts

Airport buildings consume a large 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 systems. Improvements in the infrastructure can significantly reduce the energy consumption of airports. The importance of climate conditions for this study is central, and it motivates the assessment of energy consumption changes for future climate scenarios. The software used for the work related to this OI is EnergyPlus (https://energyplus.net/). EnergyPlus is an open-source software developed by the US Department of Energy, and it is the most widely used package for *building energy simulation* (BES).

- **Objective:** The goal of this study is to investigate the potential for reducing energy consumption through infrastructure upgrading. It also clarifies how the energy demand will change in the upcoming decades, and identifies the regions which are most affected by climate change and its consequences on energy consumption.
- **Research gap to be closed**: Past studies (e.g., [19][20]) do not estimate the potential energy savings that can be introduced in a current and future climate scenario, by upgrading the infrastructure of European airports.
- **Innovations:** This study will combine results which are generated for different climate zones and for different future climate scenarios, therefore producing a novel perspective on airport infrastructure upgrades.
- **Requirements**: This study requires the use of a building energy simulation software, a realistic model for airport buildings, and reliable weather input files for present and future conditions across the European continent.
- **Limitations:** The building modelled in this work is the office building, whose energy consumption is significantly smaller than the terminal building. However, the upgrade of the terminal building would entail a much more difficult study, with limited options due to its size and complexity.

- **Geographic regions**: Europe
- **Timeline:** present - 50 years
- **Traffic sample**: Passenger traffic of a country (taken from the European airport traffic database)
- **Models**: EnergyPlus
- **Contributing partners:** Amigo, SEA

2.9.2 Implementation

This OI deals with the upgrade of airport infrastructure, which would help reduce their extremely large energy consumption. The aim is to assess the associated energy consumption reductions for the present and the future climate conditions. The study is carried out using the EnergyPlus simulation software, detailed in the appendix (see section 4.6.). The building exploited in the model is a medium-sized airport office building, which is significantly simpler to model when compared to other airport buildings, such as the terminal. The validation of the office model and its energy consumption has been obtained using data provided by SEA Milan.

In order not to limit our results to the case of Milan Malpensa, we aim at producing an overview of the energy consumption savings introduced by these measures over the entire European continent.

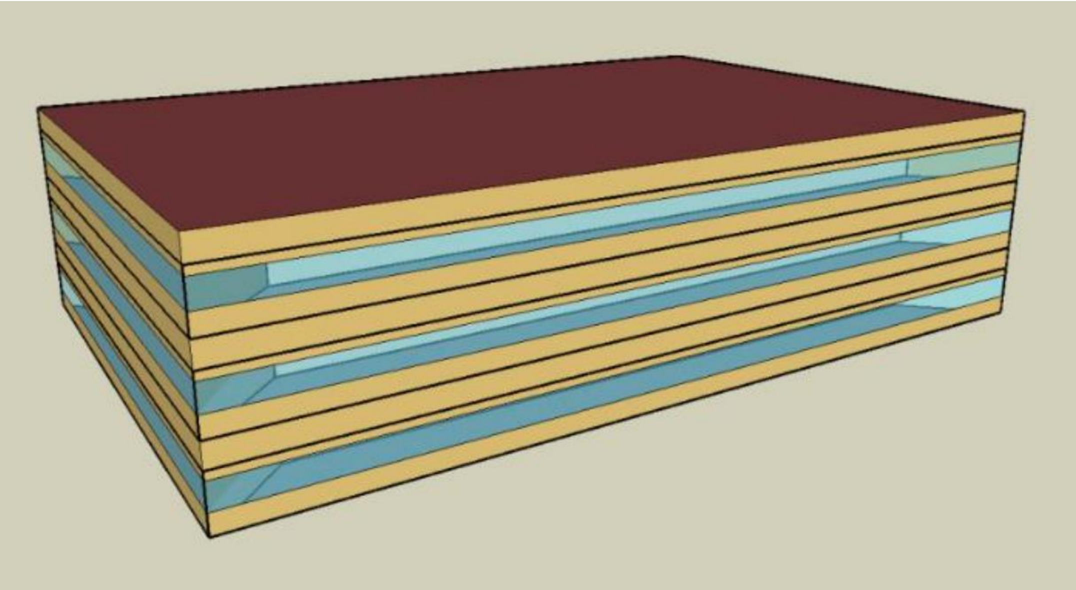

Figure 11: 3D rendering of the airport office building model used in EnergyPlus.

In particular, a set of infrastructure upgrade measures are applied to the building and the impact on the building energy consumption is assessed for each upgrade measure. The list of upgrade measures is:

- Insulation of exterior walls: The amount of heat which can flow through the exterior walls, that is the thermal conductivity, is strongly limited by the addition of an external layer of expanded polystyrene (EPS) foam insulation board. An additional advantage of EPS is that it offers the lowest thermal conductivity per euro over other types of rigid insulation.
- Optimization of windows: Given the great variability of weather conditions in Europe, we consider different upgrade measures related to the building windows. In the case of cold climates, this measure involves the introduction of triple-glazed windows, strongly effective for keeping the energy generated by the heating system in winter inside the building. For the case of warm climates, we implement reflective window films in the model, useful to reflect the solar radiation which therefore does not enter the building and interfere with the cooling system in summer.
- Introduction of LED lights: Among the many advantages provided by LED lights with respect to standard incandescent or halogen bulbs, the most relevant one for our study is their high efficiency. Indeed, an LED light typically uses 90% less energy than an equivalent incandescent or halogen bulb.

This overview needs to take into account the presence of several climate zones across the European continent [21], where a climate zone represents a classification of the type of weather that is experienced in a specific geographic region. In our study, we consider four different climate zones, which are characteristic of most of Europe. They are labelled as: warm humid, mixed humid, cool humid, cold humid.

We develop a method to quantify the impact of these upgrade measures for each European country:

1. The geographical area of a country is divided into several regions, where each region corresponds to a different climatic zone (ANSI/ASHRAE Standard 169-2013, Climatic Data for Building Design Standards). As an example, the geographical area of Spain can be split as 60% belonging to the warm humid and 40% belonging to the mixed humid climatic zones.
2. The passenger traffic of a country, a quantity taken from the European airport traffic database (https://data.europa.eu/data/datasets/43c6ugqwp92dx7vlgnzja?locale=en), is normalized to the passenger traffic of the Milan Malpensa airport. For the example of Spain, we obtain that its passenger traffic is about 11 times the one at Milan Malpensa.
3. For each climate zone of a country, its related passenger traffic can be obtained by multiplying its geographical percentage by the country's normalized passenger traffic. For the example of Spain, in the warm humid climate zone, we then obtain 11 x 0.4 = 4.4 units of passenger traffic.
4. The energy saving of each climate zone of a country can then be obtained by multiplying its passenger traffic per climate zone, as calculated above, by the energy saving of the office building belonging to this particular climate zone. For the example of Spain and the warm humid climate zone, we calculate an energy saving of 4.4 * 21 kWh/m2 = 92.4 kWh/m2.

By repeating the above steps for all climate zones of all European countries, the overview of the energy consumption savings introduced by the upgrade measures over the entire European continent is obtained.

The underlying assumption of this procedure is that the number, or more appropriately the total surface area, of office buildings of a given country is proportional to its passenger traffic. This assumption is used in step 3 where the energy savings of a single office are multiplied directly by the normalized passenger traffic, hence creating a direct link between the two.

The study will be repeated for future climate scenarios, as defined by the IPCC SRES (Special Report on Emissions Scenarios). These scenarios contain various driving forces of climate change, including population growth and socio-economic development, and encompass various future conditions that might influence greenhouse gas sources and sinks, such as the energy system and land use change. The correspondent input files for the EnergyPlus software are generated using the morphing technique, which preserves real weather sequences and is specific to an observed location. The morphing algorithms use three simple operations to modify present-day weather data: (1) a shift is applied when an absolute change to a variable is required, (2) a stretch or scaling factor when the change is projected in a percentage, and (3) a combination of both shifting and scaling may be used to adjust present-day data to reflect future projections.

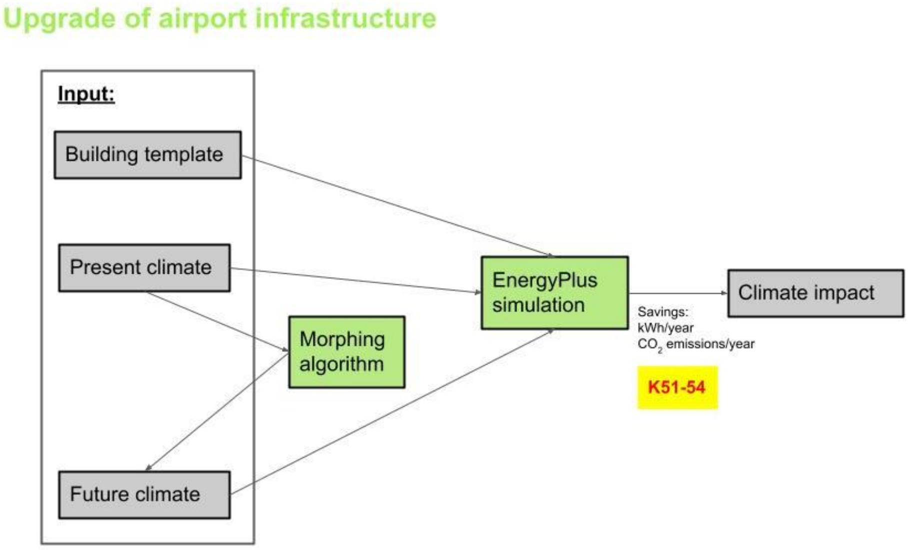

Figure 12: Workflow scheme of modelling OI Upgrade of airport infrastructure

3. Modelling the broader stakeholders impact

For a thorough assessment of the broader impact an individual OI has on the aviation domain, it is important to capture the consequences of the implementation of this OI for the stakeholders. This assessment is fundamental to understand if the OI can be acceptable by all the stakeholders or, alternatively, to determine the factors that cause resistance from some stakeholders and identify means to overcome the issues. These factors include three main aspects: (1) The costs that need to be sustained to implement an OI compared with the benefits this OI brings; (2) the impact the OI has on the human performance of the operators in the new operational environment, and (3) the social acceptance of this OI. For example, high implementation costs for aircraft operators, airports or ANSPs might translate into higher ticket prices for the passengers. Also, some OIs may cause an increase in traffic in some airspace sectors at some given times, which translates to an increase in workload and fatigue for all operators involved. Although direct modelling of these aspects is not always feasible for all the OIs, ClimOP has the ambition to assess these factors at least in a qualitative way and for a few test cases. In particular, to evaluate the Human Performance of the selected OIs, ClimOP will adopt the SESAR Human Performance Assessment Methodology, developed within the SESAR programme and adopted by standard methodology in the SESAR 1 and SESAR 2020 activities and if possible engaging stakeholder experts for the analysis. The evaluation of the implementation costs will be done following the canonical methodology of a cost-benefit analysis, as described in Sect. 3.1. The acceptance of the different OIs from the point of view of the passengers will be quantified by means of a survey (which was presented in a draft version in the deliverable 2.1 [7]) described in Sect. 3.2.

3.1 Cost-Benefit Analysis of the Operational Improvements

A cost-benefit analysis (CBA) is the process of making decisions by comparing alternative choices to determine which one has the greatest expected benefit relative to its cost. The comparison is made by identifying and measuring the expected benefits and costs of each alternative and choosing the alternative with the greatest net benefit, that is, the difference between total benefits and total costs. In order to avoid measuring each individual cost and benefit involved in a decision, it is possible to focus only on those costs and benefits that differ among the alternatives: the difference in benefits is called differential benefit, and the difference in costs is called differential cost.

The benefits of making a decision depend on the goals pursued by the organization, and are often measured in terms of cash inflows. Since these cash flows are likely to occur at different future points in time, they should be adjusted for the time value of money before they are accumulated. For example, taking the OI of electrification of ground equipment of an airport (ELEC) as a case study, a cash inflow is represented by the monetary incentives received by the airport when purchasing vehicles with low emissions: such incentives have been introduced by several EU Member States (e.g. Italy's Ecobonus, Germany's Umweltbonus, and France's Bonus écologique), often in combination with Eco-taxes that discourage the purchase of vehicles with high emissions. Not all benefits from a decision have short-term monetary consequences, and assessing their financial value can be cumbersome. For example, another benefit that should be considered in the ELEC case is the reduction in CO_2 and non-CO_2 emission, which corresponds to the ultimate goal of the airport implementing this OI. This reduction is likely to improve the airport's reputation, that is an intangible asset, and to represent a positive externality for the society, but cannot be quantified in monetary terms, as its consequences cannot be easily identified and are likely to only occur in the long term. Therefore, alternative ways of understanding whether such benefit exists have to be found: an example is the employment of passenger acceptance surveys (see e.g. Sect. 3.2), which can be used as an indicator of customer satisfaction, and of the tendency of the number of passengers to increase in an airport with an improved reputation.

Costs are defined as the use of organizational resources. The costs relevant for a CBA are opportunity costs: in fact, using a resource for one purpose represents a cost to the organization, since the same resource cannot be used for other purposes. Thus, the cost of each alternative decision can be identified and measured in terms of the foregone opportunity of a different allocation of the resources involved in that decision. Once an alternative's opportunity costs are measured, they have to be adjusted for the time value of money and accumulated.

When the used resource is cash, the opportunity cost of its usage is equal to the face value of the expended cash. In the ELEC case, the purchase prices of fuel and vehicles, the maintenance expenses, and possible Eco-taxes paid on vehicles with high emissions are used as opportunity costs. Indeed, in each alternative scenario, the airport may decide to purchase different types of vehicles, powered with different fuels and subject to different disincentives.

If the opportunity cost of a non-cash resource has to be estimated, the next best use of the resource has to be identified. For example, in the ELEC case, each vehicle is a resource: at the end of a vehicle's lifetime, the airport may either choose to sell it or to send it to a junkyard for demolition (which, under some incentive systems, such as Italy's Ecobonus, implies a monetary reward if the replacement vehicle has lower emissions). In this case, if the airport chooses to sell the vehicle, the opportunity cost is the incentive it would have received in case of demolition.

Another important type of cost are sunk costs. These costs have been incurred in the past and cannot be changed, thus being equal for all possible future alternatives. Therefore, they are irrelevant in a CBA. For example, in the ELEC case, the purchase price of any vehicle that entered the fleet before the date at which the analysis begins is not relevant for decision-making.

When dealing with costs, another important step is their allocation. Direct costs, which occur when resources are used for only one cost object, can be allocated directly to the cost object. For example, in the ELEC case:

- The purchase price of each vehicle and any Eco-tax are direct costs, allocated to the vehicle.
- Fuel prices are direct costs, allocated to each purchased unit of fuel (litre, kilogram or kilowatt-hour).

- Maintenance expenses are direct costs, allocated to each kilometre a vehicle makes.

Indirect costs require a more careful allocation, since they result from the use of resources by multiple cost objects. For example, in an airport, the electric bill cannot always be easily traced back to a specific cost object. For simplification purposes, one may consider an airport that only uses electricity to power its ground electric fleet and for lighting. Thus, part of the electricity cost is direct, since the price of each kWh used to power electric vehicles is fixed and can be traced back to each specific vehicle. The remaining part, that is, the cost of lighting, is an indirect cost. To allocate indirect costs, it is necessary to define the cost objects, accumulate the indirect costs into cost pools, define an allocation base (the measurement of a characteristic used to distribute indirect costs), estimate an application rate (the ratio between the indirect cost and the usage of the allocation base), and distribute indirect costs based on the usage of the allocation base. Using the airport lighting example, the cost object is the lighting overhead, and all its costs are accumulated in one cost pool. A possible allocation base could be the square footage requiring illumination, so the application rate is computed as the ratio between lighting costs and the illuminated area, expressed in square feet. The resulting rate is equal to the lighting cost triggered by each square feet, and can therefore be allocated to it.

3.2 Analysing the social acceptance of the Operational Improvements

The ClimOP survey aims at identifying OIs which not only mitigate the climate impact of the aviation sector, but that are also perceived as acceptable by stakeholders and primarily by airline passengers. The results will be used by the consortium to understand how much passengers are willing to accept changes in their flight experience knowing that it is for fighting climate change.

The survey will be distributed to an intended pool of at least 300 respondents via mailing lists, social media and other digital means of communication. The ClimOP Consortium intends to gather answers distributed as evenly as possible throughout the European Union.

For the realization of the survey, considering that the success of climate-friendly improvements depends on their social acceptance, a particular focus has been put on this dimension. It is essential to include an analysis of the social aspects that influence the acceptance of “green” technologies and measures, in addition to the already known technical and economic aspects. In fact, OIs that are technically and economically feasible in a given context may not be successfully implemented due to social resistance, lack of awareness of the technology, etc. The most relevant aspects influencing social acceptance of an innovative technology were in part derived from prior studies [22] [23][24][25] and were implemented with individual psychological factors, to better understand the passenger perspective towards social acceptance.

Social Acceptance is intended as a positive attitude towards a technology or measure, which leads to supporting behaviour if needed or requested by local authorities or governments.

Social acceptance, from an individual perspective, is consistently driven by attitudes which influence the behavioural intention to implement a specific behaviour (adopting OIs), intended as the degree to which a person has a favourable or unfavourable evaluation of the said behaviour [27].

Specifically, (environmental) attitudes involve awareness and concern about: the perception of climate change as an issue; the perception of the current aviation model as not sustainable and the knowledge of national and European initiatives to mitigate it. Awareness alone, however, is not sufficient to understand and predict social acceptance of green innovations.

Other individual factors co-participate in the definition of someone's acceptance. People need to have an interest in the matter (green mobility), as a central or important topic that defines their attitudes and values regarding the environment, influencing their intentions and their behaviours.

Behavioural intention, as an antecedent of behaviour, is also subject to social influence from the context, nation and community the subject lives in. For instance, a nation interested in spreading sustainable and positive behaviours, would want to share with its citizens values and norms on global and environmental issues. People who share or internalize these behaviours are the first ones to adopt new green solutions on a personal and social level, especially if, when reflecting on past experiences and anticipating future obstacles, behaviours are perceived as controllable, favourable and implementable.

Lastly, most renewable energy technologies (or operational improvements) do not compete with incumbent technologies on a level playing field, thereby making their acceptance a choice between short-term costs and long-term benefits [22]. In fact, individual factors influencing decision making are a trade-off between risks and benefits (effort, economic incentives, trust in decision-makers and other relevant stakeholders, fairness of the decision-making process etc.) in terms of adopting green solutions and is an essential step towards social acceptance.

For these reasons, starting from questionnaires developed in the context of the acceptance of renewable energies [26] the survey has been structured as follows:

- Background information: that focus on the country they live in and their travel habits (i.e., the most used mean of transportation, the favourite mean of transport and the frequency with which they were taking flights before the pandemic);
- Acceptance information: attitudes (perception of climate change as an issue, attitudes regarding environmental global issues, intentions to take action); awareness (knowledge about European/governmental initiatives); perception of the climate impact of aviation (share of aviation that impacts on climate change as a human activity); interest in green mobility (intended in rethinking their own mobility); social influence (comply to OIs if the majority of passenger would do so); decision making, acceptance and adoption (in favour of public innovations; intention to use and adopt the technology);
- Regulatory OIs information: the degree to which the changes introduced with the OIs are acceptable to passengers, for example: higher ticket prices, longer or multi-segmented flights, baggage restrictions, less frequent and more crowded flights, and the attitude towards more control on the climate impact of aviation by the government bodies.

To assess social acceptance of the operational improvements, the items of the questionnaire will be merged according to the categories mentioned above: attitudes, awareness, interest in green mobility, social influence and decision making. They will be analysed according to the Theory of Planned Behavior [27], in which a behavioural intention, in this case to accept and adopt operational improvements, is influenced by those dimensions. A linear regression will be performed to identify the variables able to predict passengers' social acceptance of the OIs. Descriptive statistics will be used to observe the degree of acceptance of the proposed OIs. The final list of questions of the ClimOP social acceptance survey is presented in Sect. 4.9.

4. Annex – Model and Tool Overview

The following section gives a short overview about the available model tools of various contributing partners. The following tools focus on different purposes like trajectory simulation, emission modelling and gridding, climate impact assessment, direct operation cost estimation and network effects. The tools are planned to be applied and advanced during the introduced workflows of modelling the climate impact of the OIs.

4.1 AirClim

The climate-chemistry response model AirClim combines results of detailed climate-chemistry models, with emission data to obtain time series of radiative forcings and temperature changes caused by these emissions. These climate-chemistry model results describe the impact of a local emission on the radiation budget, e.g. the change in contrail-cirrus radiative forcing due to air traffic, and eventually on the global mean near surface temperature [28].

- **Method:**
  - Climate-Chemistry Response model based on detailed chemistry climate model simulation
    - Unified emissions of NO_x, H_2O and flown distances
    - 3-year simulation for each location
    - Calculation of chemical perturbations, contrail coverage, radiative forcing and methane lifetime change
    - Response to local perturbation is simulated
  - Simplification of a complex climate-chemistry model (E39/CA) to enable efficient computing times
    - Any emission profile can be approximated by a linear combination of the perturbations
    - Any response to an emission profile can then be approximated by the linear combination of the individual perturbations

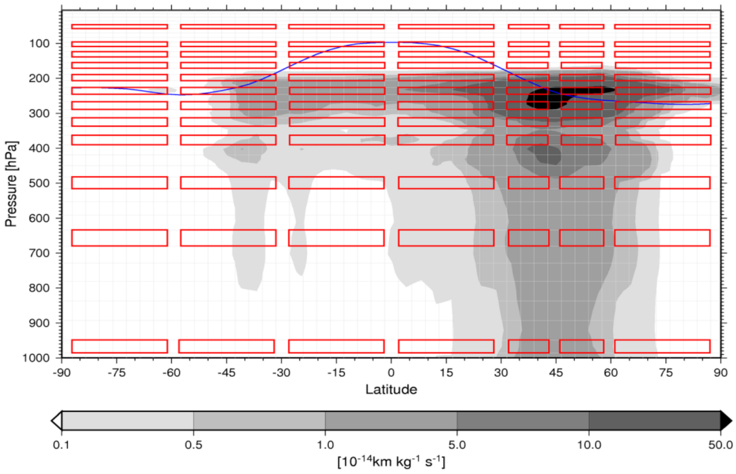

Figure 13: AirClim - Emission locations for pre-calculated look-up table [29]

4.2 Airport-Centric Queuing Network Model (QNM)

- **Purpose and method**
  - Simulation of delay/uncertainty propagation over the European Airport Network
  - Evaluation of the impact of local delays or new schedules on the network

  - Model based on queue network
  - Capacity constraints of airports based of historical records
  - Input: Departure times + capacity reduction (if any) + flight durations (optional)
  - Output: Delays
  - applied in the workflows of Strategic planning and Climate-optimised flight planning

- **Examples**

Airport	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Total Delay(min)	% of Flights with +15 min delay	Total Delay(min)	% of Flights with +15 min delay	Total Delay(min)	% of Flights with +15 min delay	Total Delay(min)	% of Flights with +15 min delay
EDDF	181	0.1	1389	1.2	18969	52.8	18404	51.6
LFPG	186	0.1	1411	1.1	1681	0.8	465	0.8
EGLL	1069	0.2	100536	74.6	1519	1	1411	1
EHAM	211	0.2	1627	1.5	3969	0.9	415	0.7
LTBA	3200	0.2	3572	0.7	3374	0.6	3261	0.5
EDDM	78	0.1	1223	1.4	322	0.9	286	0.9
LEMD	409	0.4	1461	1.5	590	1	563	1
LIRF	122	0.2	1193	1.5	260	0.6	241	0.6
LEBL	145	0	806	0.9	346	0.7	312	0.7
LOWW	231	0.3	814	1.1	496	1.7	475	1.7
EDDT	47	0	848	2.2	266	1.3	247	1.3
EIDW	88	0	2709	4.6	192	0.6	165	0.6
EGPH	44	0	1898	5.9	121	0.3	85	0.3
EGPF	211	0.4	1464	4.7	236	0.4	211	0.4
EGPD	38	0	1355	5.3	111	0.9	88	0.9
EDDV	31	0.7	808	2.2	150	3.7	137	3.7
EDDP	1	0	144	0.9	121	3.6	116	3.6
Major Airports (102 Airports in Network)	14092	0.36	152798	4.05	45738	2.98	38509	2.87

Scenario 1: Nominal Condition
Scenario 2: 25% Capacity Reduction in EGLL
Scenario 3: 25% Capacity Reduction in EDDF, LFPG and EHAM
Scenario 4: 25% Capacity Reduction in EDDF

Figure 14: Selected Applications: The impact of local capacity reductions on the network

4.3 AirTraf

AirTraf is a tool that performs global air traffic simulations, including effects of local weather conditions on the emissions. AirTraf was developed as a new submodel of the ECHAM5/MESSy Atmospheric Chemistry (EMAC) model. Air traffic information comprises Eurocontrol's Base of Aircraft Data (BADA Revision 3.9) and International Civil Aviation Organization (ICAO) engine performance data. Fuel use and emissions are calculated by the total energy model based on the BADA methodology and Deutsches Zentrum für Luft- und Raumfahrt (DLR) fuel flow method. The flight trajectory optimization is performed by a genetic algorithm (GA) with respect to one of the 8 routing options. Optimal flight trajectories for cruise flight phase and global fields of flight properties are output. Trajectory conflicts and operating constraints are not taken into account, however.

4.4 AOMAS

- **Purpose and method**
  - Strategic network planning of an airline based on the OD pair demand
  - Requires passenger demand for all OD pairs and airline available fleet
  - Uses dynamic programming to find the best network structure and flight schedule based on the input data
  - Supports point-to-point and hub-and-spoke network structures
  - It can take into account the airport slots, curfew hour and other important operational limitations and constraints
  - Output: network structure, flight schedule and aircraft rotation according to the fleet and OD pair input data
- **Visualisation examples**

  This model is currently is under development and still there is no output examples. The results will be presented in the following deliverables.

4.5 EGO Model

- **Purpose of the model**

The purpose of the tool is to calculate the variation of GHG emissions at an individual airport if the ground fleet were to be completely electrified, and to estimate the impact on climate of this variation.

- **Modifications to the model input data**

The model inputs have been reiterated twice. At first the model was developed starting from the detailed Ground Support Equipment (GSE) data of SEA Milan airports (Malpensa and Linate). This dataset includes all details about the SEA ground fleet and hence the model was implemented following the steps described in Sect. 2.8 and it is applicable to any airport which provides the required input data.

Subsequently, the model was expanded to enable an estimate of the GHG emissions also in cases where the detailed composition of the ground fleet is not known. A first step in this direction consisted in including the option where the only input is the total number of vehicles in the airport ground fleet. To achieve this, two assumptions need to be made:

1. Milan airports are "typical airports" and thus their vehicle-type and fuel-type distributions of their ground-operations fleet are representative of those of all airports.
2. The number of vehicles in each size category scales equally with the size of each airport fleet. Hence, the proportion of vehicles in each size category remains the same independently of the fleet or airport size.

In addition to the assumptions made above, an additional constraint exists in the EGO model. Some of the specialist large vehicles do not have electric equivalents to upgrade to, for example snow trucks used in winter to clean the airport ground. SEA's plan is to replace these vehicles with hydrogen-powered alternatives to reduce emissions. For the sake of simplicity, in our model electric vehicles of similar size and energy consumption have been used instead. The hydrogen vehicles could be considered further into development.

Subsequently, another option was added to estimate the climate impact of an airport by simply giving the total number of flight operations (i.e. departures and arrivals) in a year at that location. This option was enabled when a table was acquired containing operational information for a large number of worldwide airports, and it was implemented in the form of a dropdown selector. The underlying assumption is that the number of ground vehicles at a given airport scales linearly with the number of flight operations at that airport. If this is the case, then the number of vehicles of each size category at any airport can be computed by interpolating between the number of flights at Malpensa and Linate in 2019, the reference year chosen for the ground fleet composition and flight operation data. Future interactions with airport stakeholders will be taken as an opportunity to test and validate the three above-mentioned assumptions, especially in the case more data is acquired about the ground fleet at other locations, and to consequently improve this model.

- **Outputs**

The following Table 1 summarises the output of the EGO model in the option where the only available information about the airport is the total number of flight operations. Should more information be available for an individual airport, this data would be used as a form of validation and possibly refinement of the model predictions.

Table 1: Model outputs

Fleet Values	Economical Values	Graphs
Number of vehicles, total and in each category. (Validation)	Fuel cost	Progressive Greenhouse gas emissions for both fleets over time.
Kilometres driven per year, total and in each category.	Maintenance cost	Progressive climate impact on earth temperature if upgraded to electric fleet.
Fuel consumption in Litres, total and each fuel type.	Progressive costs of upgrading the electric fleet.	Progressive costs of up-grading the electric fleet.
Energy required to power a synthetic fleet, in Kilowatt hours per year.		
Energy required to power a synthetic fleet, in Kilowatt hours per year.		

- **Visual design**

After the collection of KPIs and inputs, the visual aspect of the tool had to be outlined before implementation. The first visual prototypes of the tool were designed using Figma.com, a web-based, collaborative design tool, alongside the Python library's in-built guidelines and components.

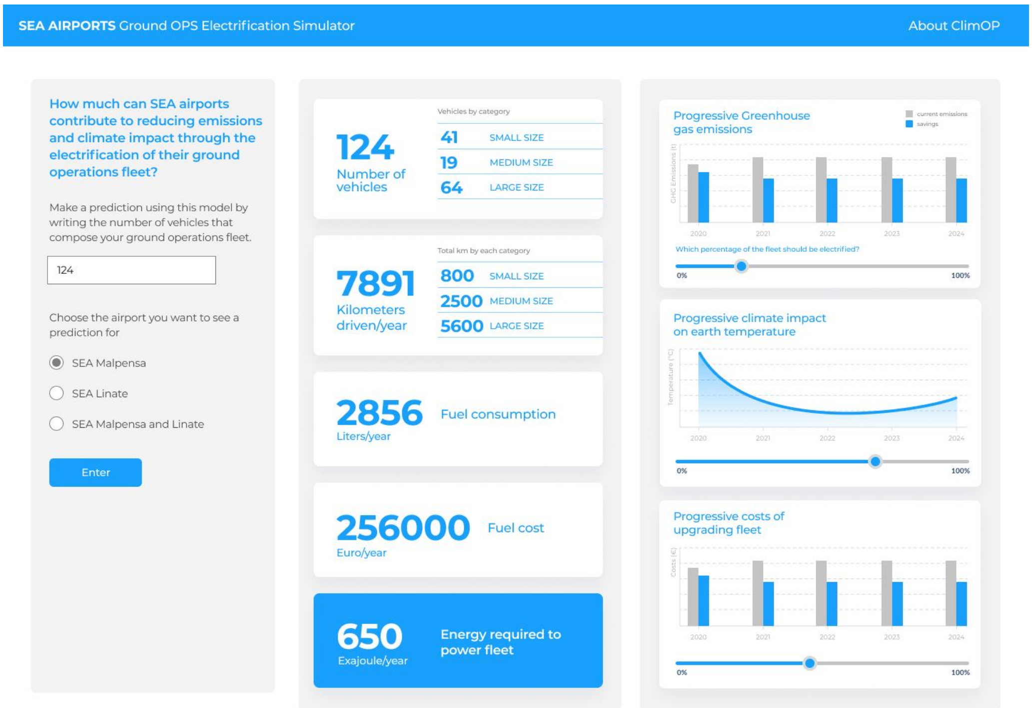

Figure 15: Visual prototype displaying arbitrary data of a generic airport.

In the tool's current state, the inputs consist of an integer form for the total number of vehicles in the fleet, a dropdown for all airports, and a set of radio buttons for SEA's airports. The interface accommodates the outputs in either numbers or graphs depending on the data. There are three graphs on display. The first graph shows a comparison between the greenhouse gas emissions of the current fleet and the synthetic fleet in the worse-case electrical energy sourcing scenario. When clicked, the graph displays greater detail, namely the GHG emission chemical breakdown of all the different gases, as well as the scenarios for the different sources of energy production. The second graph displays the climate impact over time. More specifically, how global temperature is affected by the change into a fully-electric fleet. It is expected to be a very slight variation. A click on the graph opens an expanded view where the change in radiative forcing is shown. The third and final graph displayed on the interface is a graph of the progressive costs of upgrading and maintaining the electric fleet.

- **Tool implementation**

The model is built fully in python and utilises the flask framework alongside the dash library for visualisation tools, and the numpy library for data handling.

- **Cost-benefit analysis**

The financial data used to perform the cost-benefit analysis, as well as the assumptions of price amendments after 2025, were mostly taken from the data sheets and slides provided by SEA. In a few cases, where information was incomplete, additional assumptions had to be made. This was the case of purchase prices and maintenance costs of airport specific and winter vehicles: such values were simulated by taking the means of purchase prices and maintenance costs of the other vehicles falling into the "large vehicle" category (busses and trucks).

Other values that were not provided by SEA are those of European fuel prices, since SEA limited the data to the Italian environment. As the ultimate goal of the analysis is to be applied to all EU airports, fuel prices had to be adapted, and the necessary information to do so was retrieved from the tolls.eu website (https://www.tolls.eu/fuel-prices). Since the numbers provided by SEA for Italian prices referred to 2019 values, prices from the same year were considered for all other countries.

In the analysis, the cost of purchasing new vehicles was adjusted for the incentives or disincentives that may arise with the purchase. In Italy, the purchase of new electric vehicles is incentivized through Ecobonus (https://ecobonus.mise.gov.it/), whereas vehicles that surpass a certain threshold of emissions are subject to the so-called "Eco-Tax" ("Ecotassa" in Italian Law nr. 178/2020, art. 1 sect. 1042-bis.).

Another crucial assumption that was made concerns market interest rates, which have been set to zero. Although future interest rates are subject to uncertainty, numerous macroeconomic studies, including Moody's forecast [30], are anticipating low interest rates for the next several years, and this cost-benefit analysis is based on their assumptions.

- **GHG emissions**

The following table from [16] shows GHG emissions for several production methods:

Table 2: Greenhouse gas emissions per source used in electrical energy generation.

	GHG emissions (kg/kWh)			
Source	**CO_2**	**SO_2**	**NO_x**	**CO**
Coal	1.18	0.0139	0.0052	0.0002
Petroleum	0.85	0.0164	0.0025	0.0002
Gas	0.53	0.0005	0.0009	0.0005

In its preliminary version, the EGO model calculates the energy necessary to power the fully-electric fleet using an average mix of generation sources representative of the EU area. One possible improvement of the EGO model will be to include multiple combinations of sources. Ideally, the biggest reduction of GHG emissions is achieved if the electric energy is produced by renewable sources close to or at the airport premises. A review of the possible options for on-site electricity generation can be found in the deliverable 1.2 of ClimOP [31].

4.6 Emission and Gridding Model

- Input: Trajectories (time, position, altitude, fuel consumption)
- Output: Emission grids (NO_x, HC, CO, H_2O, CO_2, SO_2)
- applied in the workflows of the OIs of Free Routing and Wind/Weather Optimized Flight Planning

The model uses the ICAO Engine Exhaust Emissions Data Bank [32] to obtain the emission indices of NO_x, HC, CO for several aircraft engines during the LTO (Landing and Take-off) cycle. The emission factors are adapted to altitude using the Boeing Method 2 [33]. In this way, the emissions for the pollutants NO_x, HC, CO can be estimated. The model also assumes that the emissions for the pollutants H_2O, CO_2, SO_2 are proportional to the fuel burn with specific coefficients as presented in the study [34]. In this way, the released emissions for the given trajectories are calculated. Then, the air traffic emissions are projected into a grid structure to obtain 3D emission distributions.

4.7 Energy Plus

EnergyPlus is the U.S. Departments of Energy’s dynamic building energy simulation engine for modelling building, heating, cooling, lighting, ventilating and other energy flows. It is one of the most robust and used energy simulation tools available both at academic and commercial levels. It is open source and freely downloadable and it is compatible with Windows systems and Linux & Mac. The main peculiarity of the tool is that it computes the heat loads through the air heat balance of the enclosure considering the simultaneous calculation of radiant and convective effects at both in the interior and exterior surface during each time step. EnergyPlus is based on ASCII text input and output files and is a stand-alone simulation program without a ‘user-friendly’ graphical interface, although various third party interfaces have been developed in different countries in the past to overcome the limitations or simplify the use of the tool.

Weather boundary conditions can be inserted as a TMY (Test Meteorological Year) file of a certain location, that is all yearly climatic values (8760 hourly values) of quantities such as dry bulb air temperature, wet bulb air temperature, air humidity, etc., which are then interpolated by the software at the time step of calculation. For the OI that deals with the upgrade of airport infrastructure, EnergyPlus is used in the OI of Upgrade of the airport infrastructure according to energy efficient criteria to model an idealized airport office building with current infrastructure conditions, which is then modified by the insertion or replacement of some of its components, through the standard graphical interface.

4.8 GRIDLAB (Global air traffic emission distribution laboratory)

- **Purpose and method**
  - Calculation of air traffic emissions of flight trajectories based on the fuel flow and fuel flow correlations

- Numerical gridding of air traffic emissions to get 3D emission distributions on regional and global scale
- appropriate input data for aviation climate impact assessment and important tool for environmental studies
- High resolution 3D emission inventories: horizontal resolution: up to 0,25° x 0,25°, vertical resolution 1000ft
- Non-linear emission simulation based on fuel flow correlation methods
- Input: georeferenced flight trajectories and altitude and fuel flow profile
- Output: CO_2, H_2O, NO_x, SO_2, CO, volatile organic carbons, Soot emissions in, output file in netCDF binary grid format, a common data format in climate research
- applied in the workflows of Flying Low and Slow, Climate Optimised Intermediate Stop Operations and Climate Optimised Flight Planning

- **Visualisation examples**

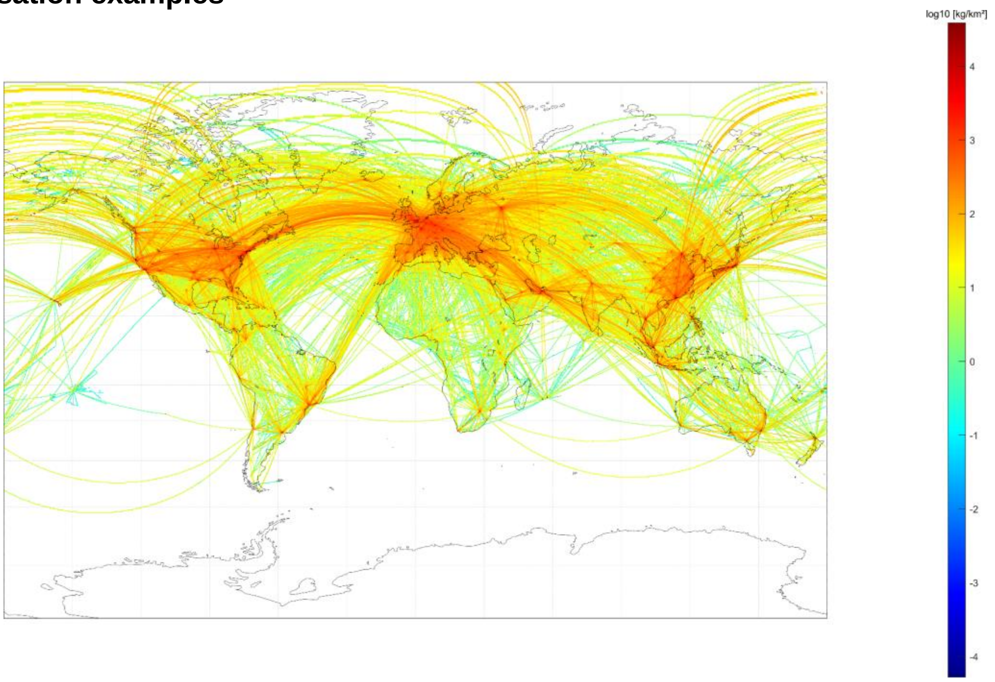

Figure 16: Vertically aggregated Latitude-Longitude CO2 emission distribution of global air traffic in week 30 in 2015

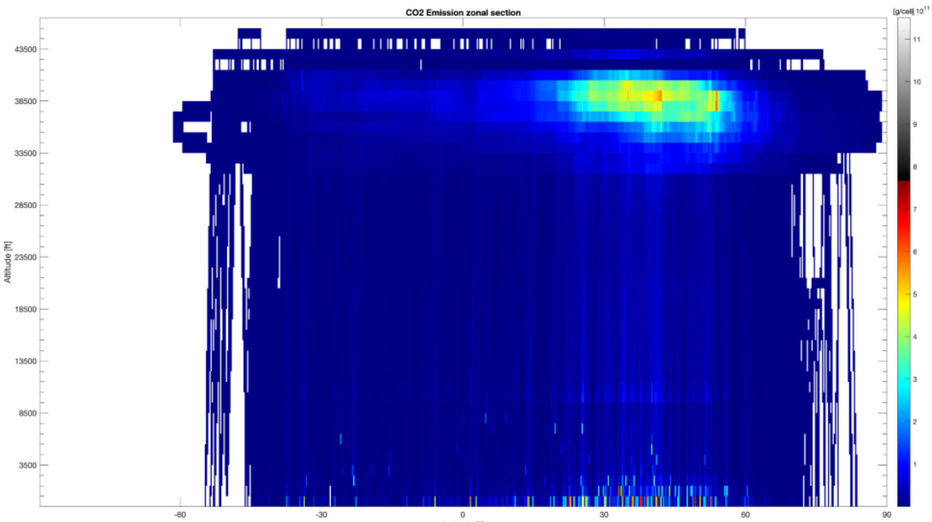

Figure 17: Vertically aggregated Latitude-Altitude CO_2 emission distribution of global air traffic in week 30 in 2015

4.9 Survey to assess the social acceptance of the Operational Improvements

The following table shows the questions of the survey to assess the social acceptance of the OI analysed in ClimOP. This survey is a development of the list of questions presented in D2.1. In the present, refined version, the questions are organised in areas which will make it possible to correlate the response to individual questions to the specific habits of the respondents and their general attitude towards climate and environmental issues.

Table 3: Questionnaire for social acceptance of Operational improvements

Area	Question	Answer
Background Info	1. What is your age?	Open
	2. What is your gender?	Closed
	3. In which country did you spend most of your lifetime?	Open
	4. What is the highest degree or level of school you have completed?	Open
	5. What is your average net income?	Open
	6. What is your profession?	Open
Travel Habits	7. Which mean of transport do you use the most?	Closed
	8. Which is your favourite mean of transport?	Likert
	9. Before the pandemic, how often did you travel by airplane?	Closed
Perception Climate Change As Issue	10. How much do you feel the following are environmental issues? a. Acidifications of rains and oceans b. Air pollution c. Raising of global temperatures d. Extreme weather conditions e. Environmental resource exploitation f. Loss of biodiversity g. Pollution of rivers and seas h. Soil pollution i. Traffic congestion j. Waste disposal	Likert
	11. How much do you feel climate change as a global issue?	Likert
	12. How much do you think climate change is an issue for the people around you?	Likert
	13. How much are you in favour of taking actions to cope with climate change?	Likert
Environ. Friendly behaviour	14. How much does the awareness of environmental-responsible behaviours influence your decisions?	Likert
	15. On a daily basis, which decisions do you take with the aim of preserving the environment?	Open
Awareness	16. Could you name any European initiatives to mitigate climate change?	Open
	17. Could you name any initiatives taken at the National level by your country to mitigate climate change?	Open
	18. Could you name any initiatives in aviation to mitigate climate change?	Open
Perception Climate Impact Aviation	19. If the total impact of human activities on climate change today is set to 100, how much do you think is the share of aviation?	Closed
	20. If the total projected impact of human activities on climate change in 2050 is set to 100, how much do you think will be the share of	Closed

	aviation?	
	21. How much Aviation should change and introduce measures to reduce its climate impact?	Likert
Interest Green mobility	22. How much would you be interested in rethinking your mobility to mitigate climate change?	Likert
	23. How important would it be to you to take a flight aimed at reducing emissions of Greenhouse gases?	Likert
OIs	24. Flying low (and slow) Many aircraft tend to fly at an altitude of above 10,000m, where the emissions of greenhouse gases are particularly impactful for climate change. Airlines could lower their flight trajectories to avoid regions of the atmosphere that are particularly climate sensitive. If all aircraft flew at lower altitude, the impact of aviation GHG emissions on climate change could potentially be reduced by *X%*[1]. a. TODAY, the ticket for a typical flight from Rome to London (or similar European flight) costs approximately 100€. How much would you be willing to spend for a flight that travels at lower altitudes, knowing that this has a lower impact on climate? b. TODAY, the ticket for a typical flight from Paris to San Francisco (or similar transoceanic flight) costs approximately 800€. How much would you be willing to spend for a flight that travels at lower altitudes, knowing that this has a lower impact on climate?	Likert *(options in the range from "same price" to "twice the price")*
	25. Flying (low and) slow → longer flights The GHG emissions of aircraft depend on the cruise speed. Up to a certain extent, on average the faster an aircraft travels, the more fuel it burns and consequently the more GHG it emits in the atmosphere. Reducing the typical cruise speed by *X%*[1] would reduce the emissions of GHG by *Y%*[1]. However, this would also increase the duration of the flights. a. Knowing that this would be beneficial to fight climate change, how much would you be in favour of taking *3.5 hours instead of 2 hours and 40 minutes*[1], to fly from Rome to London (or similar European flight)? b. Knowing that this would be beneficial to fight climate change, how much would you be in favour of taking *15* hours instead of *12 hours* [1], for a Paris-San Francisco flight (or similar transoceanic flight)?	Likert
	26. Strategic planning/intermediate stop-over An optimised network of connections between airports can potentially reduce the impact of aviation of GHG emissions on climate by *X%*[1]. However, this would imply that direct connections could be cancelled and replaced by multi-segment flights. Knowing that this would be beneficial to fight climate change, how much would you be in favour of having 2/3-segment flights instead of direct flights to reach your destination?	Likert

[1] Exact numbers for the survey will be derived from the respective OI studies and provided once estimations are available.

	27. Strategic planning/intermediate stop-over How much would you be in favour of taking segmented flights with longer stop-overs to spend some time exploring the intermediate city?	Likert
	28. Weight limitations/baggage restrictions (no OI explicitly on this) The aircraft emissions of GHG are proportional to the weight of the aircraft. If you reduce the weight of an aircraft *from Rome to Helsinki by X kg*[2], the GHG emissions of this flight would be reduced by *Y%*[2]. This could be achieved by allowing passengers a maximum of 3kg of luggage (i.e. just a small hand baggage). Knowing that this would be beneficial to fight climate change, how much would you agree to baggage limitations?	Likert
	29. Strategic planning (merge flights) → larger aircraft + less frequent, crowded flights If the frequency of flights were to be reduced to always guarantee that they are fully loaded, and larger aircraft were to be used on popular routes, the emissions of GHG would decrease by *X%*[2], reducing the contribution of aviation to climate change by a *factor of Y*[2]. a. Knowing this, how much would you agree to have less frequent flight connections? b. How much would you agree to travel on larger aircraft fully booked?	Likert
	30. Electrification of ground operations Several airports are currently transitioning to completely electric ground operations, which reduces the local GHG emissions from ground vehicles to almost zero. In addition, these airports are committed to producing and using renewable energy, so that they are effectively climate-neutral. How likely is it that you would choose to travel from an airport, if you knew that this airport is climate neutral?	Likert
Regulatory OIs	31. Would you sign a petition to foster regulations that promote flights that are more climate-friendly (e.g., tax discounts for aircraft that avoid climate-sensitive trajectories)?	Likert
	32. If the government put in place a transparent and objective system to assess the “climate friendliness” of the operations of different aviation companies, would you consider choosing your flights based on the climate reputation?	Likert
Social Influence	33. Would you ask for advice before taking a flight which implements operational improvements to mitigate its impact on climate?	Likert
	34. Would you decide to take a flight with operational improvements if the majority of the people you know were doing so?	Likert

4.10 Trajectory Calculation Module (TCM)

Purpose and method.

- Calculation of realistic ATM-compliant 4D trajectories
- Determination of mission KPIs, such as burn fuel, flight time

[2] Exact numbers for the survey will be derived from the respective OI studies and provided once estimations are available.

- As part of air traffic simulation, e.g. for the analysis of aviation's environmental impact
- Various aircraft performance models can be used, e.g. BADA 4.2
- Fast-time, forward integration of aircraft state based on simplified point-mass equations of motion ("Total Energy Model")
- Implemented in MATLAB, flexible and modular research environment
- Increased computational efficiency through adaptive sampling time method
- ISA/Non-ISA conditions can be modelled
- Vertical constraints: typical flight segments
- Flight level and speed schedule can be easily adapted
- Target and exit conditions to define control laws for each phase
- Lateral route definition:
  - Great circle mode: direct OD connection
  - Airport 3- and 4-letter code format
  - Input of detailed lateral flight plan (ICAO field 15)
  - Optional curved flight mode
  - Navigation based on WGS-84 geodesics
- Outputs: Complete history of aircraft state along flight, mission KPIs, flight visualization

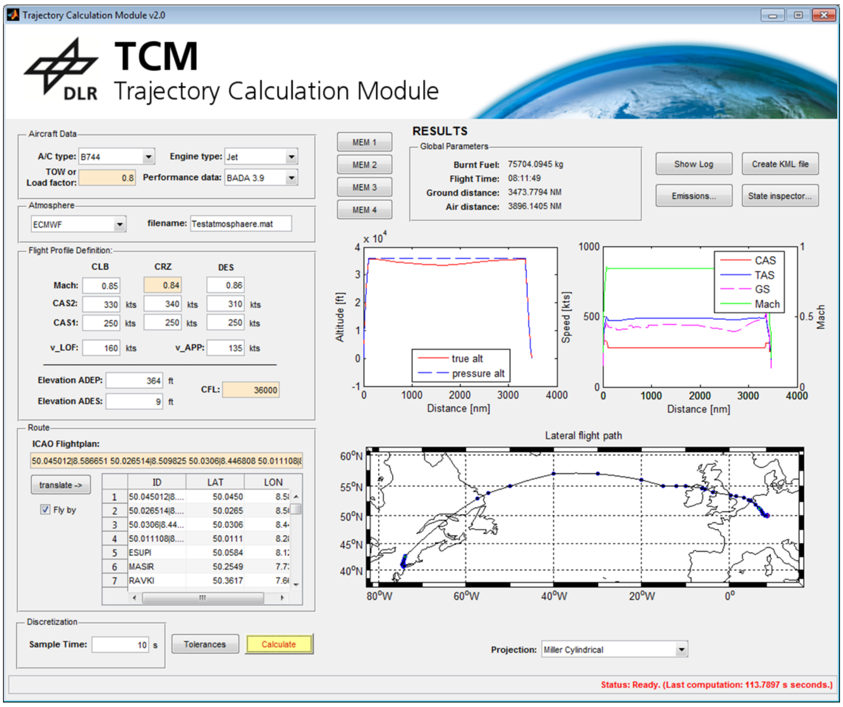

Figure 18: Graphical user interface of TCM showing a flight between Germany and the US east coast

4.11 Trajectory Generation Tool (TGT)

- **Purpose and method**
  - Generation of flight trajectories according to flight plans
  - Simulation of aircraft dynamics with a set of differential equations
  - Aircraft performance model based on BADA
  - Generation of the required control inputs to follow the trajectory between specified waypoints

- Calculation of fuel consumption during flight
- Input: A set of waypoints (latitude, longitude, altitude)
- Output: Trajectory (time, position, altitude, speed, fuel consumption)

- **Examples**

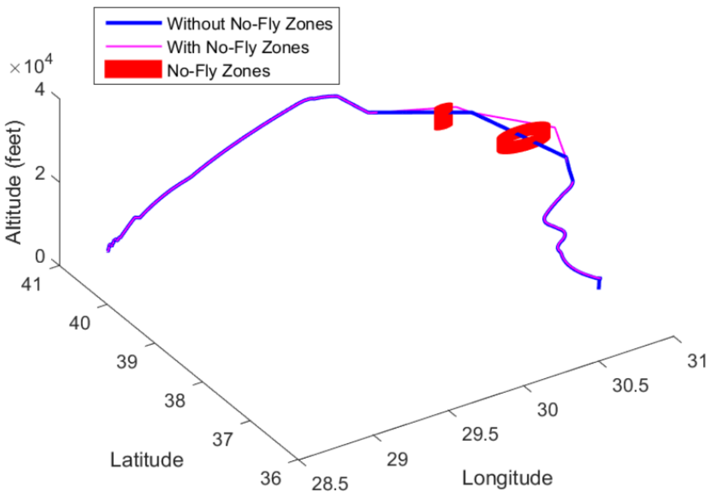

Figure 19: Generated trajectory from LTBA to LTAI: "PIMAV1S KARGI AFYON LEMDA KUMRU1R"

4.12 Trajectory Optimization Model (TOM)

- **Purpose and method**
  - Calculation of optimized aircraft trajectories for flight planning [35]
  - Application of Optimal Control Theory to solve unconstrained optimization problem
  - Focus on the environmental impact optimization
  - The aircraft motion is described by means of state variables x(t) which can be influenced by control variables u(t). A trajectory is considered optimal, if the temporal development of the control variables u(t) leads to a minimization of a cost functional J while both, the dynamic constraints as well as the boundary conditions of the state and control variables are fulfilled.
  - Heading, acceleration and throttle setting used as control vector
  - Cost functional J is defined as the weighted sum of the fuel consumption and the climate impact expressed as average temperature response (ATR) over 20 years which is represented by the algorithmic Climate Change Functions (aCCFs). Also, the fuel consumption and the resulting climate impact are normalized with respect to the corresponding reference values.
  - In order to determine the pareto-optimal solutions of the optimization problem, the weighting factors c_{Fuel} and c_{ATR} are varied between 0 and 1.

$$\boldsymbol{J} = c_{\mathrm{Fuel}} \cdot \underbrace{(m_f - m_0)}_{\text{Fuel burn}} \cdot m_{\mathrm{Fuel,ref}}^{-1} + \cdots$$

$$\ldots c_{\mathrm{ATR}} \cdot \underbrace{\int_{t_0}^{t_f} (\mathrm{aCCF}_{\mathrm{CO_2}} + \mathrm{aCCF}_{\mathrm{H_2O}}) \cdot \mathrm{FF} + (\mathrm{aCCF}_{\mathrm{O_3}} + \mathrm{aCCF}_{\mathrm{CH_4}}) \cdot \mathrm{EI}_{\mathrm{NO_x}} \cdot \mathrm{FF} + \mathrm{aCCF}_{\mathrm{Contrails}} \cdot v_{\mathrm{TAS}} \, \mathrm{d}t}_{\mathrm{ATR}} \cdot \mathrm{ATR}_{\mathrm{ref}}^{-1}$$

$$c_{\mathrm{Fuel}} + c_{\mathrm{ATR}} = 1; \; c_{\mathrm{Fuel}}, c_{\mathrm{ATR}} \in [0,1]$$

- Dynamic constraints define the aircraft motion (equations of motion of a point mass aircraft with variable mass and three degrees of freedom assuming a spherical earth)
- For solving the continuous optimal control problem is transformed into a discrete nonlinear programming problem (NLP) and solved by an NLP solver.
- Input: state variables at initial point (i.e. geographic position, altitude, speed, mass) and at final point, constants for dynamic constraints evaluation and path variables
- Outputs: Complete optimum 4D trajectory including aircraft state along flight (e.g. position, altitude, speed, mass, fuel flow, emissions), pareto frontier for different weighting factor combinations

- **Example**

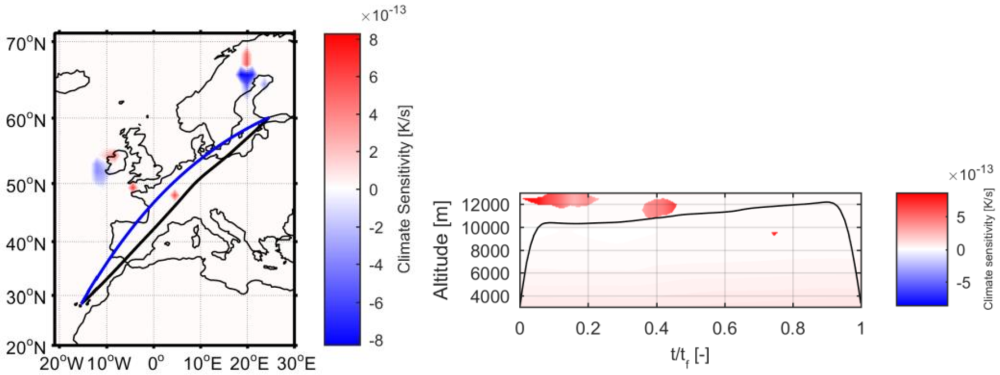

Figure 20: Climate optimized trajectory for flight EFHK-GCLP (left: horizontal map; right: vertical flight profile; blue line: great circle) for a fuel penalty of 0.1% from project ATM4E [36]

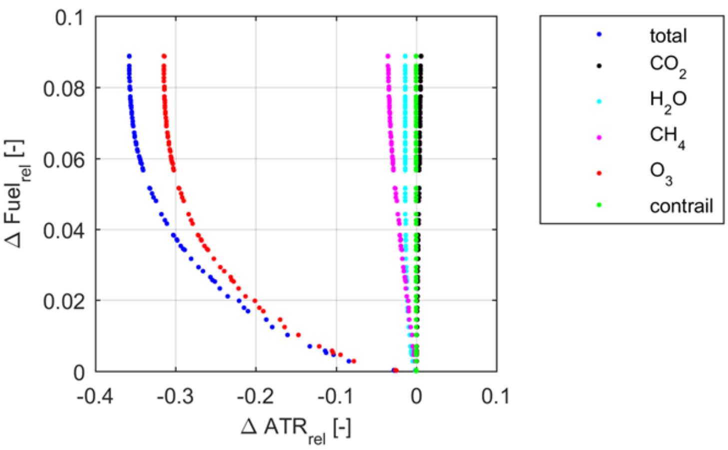

Figure 21: Pareto front of trip fuel increase over ATR reduction potential for the flight UBBB-ELLX from project ATM4E [36]

4.13 Trajectory Optimization Tool (TOT)

- Input: Initial condition, final state, objective function
- Output: Trajectory (time, position, altitude, heading, speed, fuel consumption)

The tool generates an optimized trajectory by transforming the flight planning problem into an optimization problem. The aircraft dynamics, performance limits, and wind information are considered during the optimization process. And, the performance parameters are obtained from BADA.

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