Climate assessment of innovative mitigation strategies towards operational improvements in aviation

D2.4 – Report on the climate impact of the second set of operational improvement options

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ClimOP Consortium

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Executive summary

Deliverable 2.4 "*Report on the climate impact of the second set of operational improvement options*" presents the results of the second iteration of the assessment of the selected operational improvements (OIs). The second assessment focuses on the same nine OIs as the first one. Such OIs cover three different categories: network-related OIs (two OIs), trajectory-related OIs (three OIs), and ground-related OIs (three OIs). In addition, three scenarios, combining different OIs within the category, are presented. These scenarios are aimed to highlight the synergies between different OIs. The assessments presented in this deliverable include both climate and non-climate KPIs. The climate KPIs are specific of each OI, but for all of them the Average Temperature Response on a 20-year time window, ATR20, is calculated. The non-climate KPIs investigate the impact of different stakeholder, including airlines, airports, ANSPs and passengers. The impact of the OIs on the stakeholders is analysed from different points of view: the operational, economic, safety and human performance perspectives. Such analysis was possible thanks to the participation in the ClimOP activities of IATA and SEA Milan, as partners in the project, representing the airlines and airports respectively. Further activities in this respect include the discussion with the Advisory Board (AB), a workshop with 11 airports organized to test the acceptance of ground-related OIs, and an interview with Air Traffic Controllers to understand the effect of the OIs on the workload. The social acceptance has been addressed by analysing the ClimOP survey. Moreover, the analysis includes a discussion of the uncertainties of each assessment related to the assumptions at the basis of the calculations and the limits of our knowledge and modelling tools.

One of the ambitions of ClimOP is to harmonise the OI assessments such that they can be compared to design the most effective mitigation strategy in WP3. Despite all the effort put in designing the assessment approaches, the used strategies depend on the specific characteristics of the OI as well as on the adopted models. A method to make all the inflight OIs comparable is presented in this deliverable, and will be carried out in future work within the WP3 activities. For the time being, we compare ATR20 within each OI category, and discuss the impact on climate and on the stakeholders of the OIs in a qualitative manner. The climate KPIs are summarized into three categories: CO_2 climate impact, non-CO_2 climate impact and total climate impact. As an overview of the non-climate KPIs, we considered the maturity of the OI. Furthermore, we display the operational and economic impact on different stakeholders: airlines, airports and ANSPs. This comprehensive analysis paves the way to WP3. Exploring the impact on the stakeholders highlights the need for innovative policies and regulations to make the OIs fully operational. It is important to state that IATA, as a participant of this initiative on a research level, does not endorse the OIs as documented in the present deliverable. At this stage of the analysis, IATA considers the information about OIs still insufficient, and in some cases not applicable to the actual operational and market landscape of airlines.

Abbreviations

#	number of
3D	three dimensional
AC	aircraft
ACACIA	Advancing the Science for Aviation and Climate
aCCF	algorithmic climate change function
AEDT	Aviation Environmental Design Tool
ALTERNATE	Assessment on alternative aviation fuels development
AJF	Al-Jawf Domestic Airport
ANSP	air navigation service providers
AOMAS	multi-agent airline operation planning model
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASK	available seat kilometres
ATAG	Air Transport Action Group
ATC	air traffic control
ATCo	air traffic controller
ATM	air traffic management
ATR	Average Temperature Response
ATS	air traffic service
BADA	base of aircraft data
BC	black carbon
BES	building energy simulation
BOS	Boston (Massachusetts) Airport
BXR	Bam Airport
CAS	calibrated air speed
CASK	cost per available seat kilometre
CCF	climate change functions
CFL	cruise flight level
CLIM	Climate-optimised flight planning
CMIP5	Coupled-Model Intercomparison Project 5
CND	Mihail Kogalniceanu International Airport
CO	carbon monoxide
CO_2	carbon dioxide
CYL	Coyoles Airport
CYU	Cuyo Airport
DBL	Deep Blue
DDR2	Demand data repository 2

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

KLM	Royal Dutch Airlines (Koninklijke Luchtvaart Maatschappij)
KPI	key performance indicator
LED	light-emitting diode
LIN	Milano Linate Airport
LOSL	Flying low and slow
LTO	Landing and Take-off
MAD	Madrid Airport
MXP	Milano Malpensa Airport
NAFC	North-Atlantic flight corridor
NETW	strategic network planning
NCEP	National Centers for Environmental Prediction
NLR	National Aerospace Laboratory (Nationaal Lucht- en Ruimtevaartlaboratorium)
NM	nautical miles
NO_x	nitrogen oxides
OD	origin/destination
OI	operational improvement
PM	Particulate matter
ppm	parts per million
RCP	Representative Concentration Pathway
R&D	research and development
SEA	Societa per azioni esercizi aeroportuali
SETX	Single engine taxiing/ electric taxiing/ hybrid taxiing
SO_x	sulphur oxides
SO_2	sulphur dioxide
SPC	La Palma Airport
SRES	Special Report on Emissions Scenarios
T	temperature
TAP	TAP Air Portugal (Transportes Aéreos Portugueses)
TCM	Trajectory Calculation Module
TGT	Trajectory Generation Tool
TMY	typical meteorological year
TOE	tons of oil equivalent

1. Introduction

1.1 ClimOP project

The aviation industry contributes to human-made emissions primarily 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 [3]. 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 [4]. This commitment has been recently restated despite the current crisis [5]. 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, such as, from NO_x, H_2O, and contrails, 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 (WP) 2 is the iterative quantification of the potential of the OIs, selected during WP1, in mitigating the anthropogenic contribution to climate change. Both CO_2 and non-CO_2 effects, such as ozone and methane changes from NO_x-emissions, H_2O changes, contrail-cirrus coverage, and possible impacts from particulates, are assessed in terms of changes in the concentrations and the resulting average temperature response (ATR). Different modelling strategies have been adopted depending on the specific characteristics of the studied OIs. Such modelling strategies have been adjusted, during the project, to maximise the comparability between assessments of different OIs. Although large discrepancies remain, an effort has been made to harmonise the analyses and present them in a comprehensive manner. Furthermore, a preliminary assessment of non-climate KPIs has been carried out. The specific KPIs depend on the studied OIs. In general, KPIs measuring the economic, operational and technical impact of the OIs on the key stakeholders as well as qualitative KPIs covering the social, political and market acceptance of the OIs are estimated. As such, WP2 lays the foundation for follow-up activities in WP3, that is aimed at defining a body of harmonised, most-promising mitigation strategies based on the studied OIs.

1.3 Deliverable D2.4 in the Project context

Deliverable 2.4 *"Report on the climate impact of the second set of operational improvement option"* presents the results of the second iteration of the assessment of the selected operational improvements (OIs).

During WP1, the studied OIs have been shortlisted according to a multi-step multi-criteria assessment procedure described in detail in deliverable D1.3 [6]. From the original 25 OIs, 11 OIs were selected with priority, covering four different categories of OIs: Climate-optimised operation of the airline network (two OIs), Climate-optimised trajectories (five OIs), Operational and infrastructural measures on the ground (three OIs), Operational measures at regulatory level (one OI). The considered OIs were then further selected 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 impacts on climate and the KPIs/methods to evaluate its impact on stakeholders were given in D1.4 [7] and then expanded in D1.5 [8].

WP2 aims to assess the climate impact of the selected OIs from a climate perspective, including non-CO_2 effects, as well as from a non-climate point of view. This is the concluding deliverable of WP2, and collects the final results of the assessments that build on the work reported in previous deliverables. The definition of the reference scenario, including its technological and operational boundary conditions, and the selected air traffic sample is discussed in D2.1 [9]. The modelling workflow for the climate impact simulation of all the selected OIs and the corresponding adaptation of the combined air traffic scenario is described in D2.2 [10]. D2.3 [11] gathers the results of the first round of assessment of the selected OIs. Herein, we report the advancements in our analyses for the climate impact assessment for the individual OIs, and that for the scenarios integrating several OIs. Moreover, this deliverable presents the results of the non-climate KPIs, including economic, political, operational, and social evaluations.

The present document is structured as follows. An overview of the OIs is presented in Section 2, where each subsection includes a brief description of the methodology, the assessment of climate and non-climate KPIs, and a discussion on the key uncertainties for each OI separately. For a detailed description of the methods and results, we refer to Appendix A. Besides the individual OIs, a comprehensive scenario of all the ground-related OI is also included in Section 2 in the same brief way. This choice is motivated by the fact that, by presenting the results in a compact format, we enhance the comparability. Section 3 expands on the comparability of the climate KPIs on the basis of the different modelling assumptions used for the OI assessments. A first comparison of the mitigation potential of the OIs is also attempted, within each OI category. Considerations on the applicability of the OIs with respect to their impact on the stakeholders are also included. In this sense, this deliverable lays the foundation for future work carried out within WP3 aiming at defining a body of harmonised, most-promising mitigation strategies based on the studied OIs. Finally, conclusions and recommendations are collected.

2. Results of the assessment of the considered OIs

The present section provides an overview of the assessment of the impact of the analysed OIs on the climate and the stakeholders. Each subsection is dedicated to one specific OI, and includes a brief description of the methodology, covering the scope and goal of the assessment, the key hypotheses, models and data utilised, followed by the presentation of the results of climate and non-climate KPIs, and a short summary of the uncertainties related to the modelling strategy. This overview of the assessments is intended to present the results in a compact manner such that the key assumptions and conclusions are immediately apparent and easily comparable. For a detailed presentation of the results, we refer to Appendix A. Further analysis of non-climate KPIs is reported in Appendices B, C and D, where appendix B describes the general approach used for the Human Performance Assessment, appendix C presents the results of the analysis of the Acceptance Survey, and appendix D is a detailed assessment specifically focused on the impact of the inflight OIs on the airlines developed by IATA.

The second round of OIs assessment entails the analysis of three integrated scenarios. The scenarios are defined such that to find the synergies and interdependencies among OIs of the same category, namely, trajectory-, network- and ground-related OIs. The goal of this study is to estimate the cumulative mitigation potential of the OIs of the same category, as well as potential drawbacks of their integration. The results of the integrated scenarios are included in section 2.2. for the trajectory-related OIs, in section 2.4 for the network-related OIs. A separate section describes the integration of ground-related OIs (section 2.9).

2.1 Flying low and slow

To increase fuel efficiency and, among others, reduce direct operating cost (DOC), aircraft typically fly at optimum altitudes and perform step-climbs to higher flight levels with increasing flight length. In doing so, not only fuel consumption but also climate impact from CO_2 emissions is reduced as CO_2 effects are independent of the emission location. Nevertheless, the climate impact of non-CO_2 emissions, such as contrails, water vapour, and NO_x, vary with the location, altitude, time and environmental conditions of the emissions. These effects are assumed to be reduced by lowering flight altitudes to less climate-sensitive areas. As this is associated with higher fuel consumption, an additional reduction in flight speeds could diminish the resulting increase in CO_2 effects. To incorporate effects from different atmospheric boundary conditions, different meteorological and seasonal atmospheric situations and long-term climatological changes are considered in this analysis. Significant mitigation potentials can be obtained thanks to flying lower and slower (up to 13% of ATR20 in summer and 21% in winter). However, this is associated with extra fuel consumption and flight time, which influences applicability of this OI from the Stakeholders' perspective.

Methodology

The goal of this study is to assess the climate mitigation potential in terms of average temperature response in 20 years (ATR20) by flying lower and slower, and the effects on non-climate KPIs such as fuel consumption and flight times. For this purpose, cruise altitudes and speeds are lowered systematically. Besides the reference case of changing flight levels (e.g. according to ATC restrictions or fuel efficiency reasons), a limitation to a constant flight level is modelled, from which reductions of 2000ft, 4000ft and 6000ft are assumed. Cruise speed reductions of 5% and 10% of the provided BADA4 speed schedule are considered.

Flight time, fuel consumption, engine emission quantities per species, and ATR20 are calculated in the course of the simulations. For this purpose, DLR's Trajectory calculation module (TCM) is applied to simulate the four-dimensional trajectories including the fuel flow in every simulation step. Emission quantities are calculated based on fuel flow with DLR fuel flow method [12]. To compute ATR20, algorithmic climate change functions (aCCFs) according to [13] are adjusted and evaluated. For details on made assumptions in the simulation process, please refer to Appendix A1.

The analysis of the study is divided into three subsections that differ in the selected flight plan.

(1) A baseline study investigates the effects of flying low and slow for two selected specific days. For these days, flights are modelled according to actually flown point-profiles (provided by EUROCONTROL), and the real atmospheric conditions during the flights are taken into account (ERA5[1] reanalysis data provided by ECMWF).
(2) A meteorological study analyses the dependence on seasons of LOSL. For this purpose, one representative day per season is selected according to DWD classification [14], and a comparable set of flights with optimal flight levels (i.e. step climbs) and great circle routes is considered as the reference case.
(3) A climate-change study aims to investigate the effects of long-term climatological changes. Due to a variety of uncertainties in the forecasts, this part of the analysis focuses on contrail distances only and mitigating them by flying lower and slower.

Within the different sub-studies, climate-optimisation is performed on a single flight basis, i.e. the climate-optimal combination of cruise flight level and speed is selected, and these solutions are combined to assess the full mitigation potential of the flight plan. Allowed shares of extra fuel and time can be defined to provide mitigation potentials depending on stakeholders' implementation efforts.

Results

A. Assessment of climate KPIs

Climate-impact modelling confirms that the average temperature response over 20 years can significantly be reduced by flying lower and slower. For individual long-range flights in the North-Atlantic region[2], mitigation potentials of up to 64% can be seen on June 16, 2018. On an aggregated level, climate mitigation potentials of up to 13% for the representative summer day and up to 21% for the representative winter day will be achieved. When keeping additional fuel flow and time within certain limits, the following climate mitigation potentials, as displayed in Table 1, are possible. These differences can mainly be explained due to reduction of contrail warming effects. For further details, please refer to Appendix A1.

A comparison of the selected representative days shows that mitigation effects vary widely across the different seasons. Mitigation potentials in winter and spring (December and March) appear to be higher than in summer and autumn (June and September) as composition of emissions causing rise in ATR20 varies depending on the different seasons. Furthermore, we can also confirm influences of long-term climatological changes also impact the effectiveness of flying low and slow for climate mitigation.

[1] ERA5 stands for ECMWF REanalysis version 5.
[2] Applied aCCFs have been developed and validated for the North Atlantic region (75W – 5W, 80N – 30 N), but can be applied "off-design" for other geographic scopes.

Table 1: Climate mitigation potential depending on extra fuel and time allowed

	Fuel- and time-penalty	Climate mitigation potential[3]
Long range flights on June 16, 2018	1 %	- 2,5 %
	5 %	- 6,3 %
	10 %	- 6,9 %
Intra-ECAC flights on June 16,2018	1 %	- 2,7 %
	5 %	- 12,5 %
	10 %	- 14,6 %

B. Assessment of non-climate KPIs

Flying lower and slower is primarily associated with longer flight times (due to flying slower) and potentially higher fuel consumption (due to flying lower). However, the second aspect is aimed to be limited due to flying slower, so that a compromise between different effects can be achieved by, at the same time, reducing climate effects of the considered flights. Based on the study set-up, it is possible to estimate ATR reductions depending on different levels of fuel consumption and extra time allowed. Assuming a maximum allowance of 5% extra fuel and time, which is associated with a climate mitigation potential of approximately 9.9% for the flights sample on June 16th, 2018, an average increase in fuel consumption by 0.4% and flight time by 1.3% can be achieved, leading to a moderate increase in average direct operating cost (DOC). Besides potential economic disadvantages, flying lower and slower also comes along with an extended utilisation of selected more climate-friendly altitudes. However, for the selected subsample, we do not see increases by more than one third compared to the respective flight level and not more than 7% compared to the maximum observed utilisation per flight level, so that high safety levels can be maintained. An additional upgrade of Communications, navigation and surveillance (CNS) infrastructure would support low accident rates and controller workloads in case of implementing this OI. Regarding social acceptance, results of a passenger survey indicate that a slight majority of the passengers would be willing to bear the consequences of flying lower and slower in terms of additional ticket prices and additional flight time (Appendix C).

C. Discussion on uncertainties

When interpreting the climate impact of this OI as well as comparing it with others, the main uncertainties have to be considered.

- *Uncertainties in trajectory and emissions modelling*: The main uncertainties derive from flight performance assumptions based on BADA4 as well as weight uncertainties, currently assumed with an average European load factor. Also, inaccuracies in atmospheric data can influence the achieved results. All in all, these uncertainties are estimated to have a low impact on fuel flow, flight time and emission quantities.
- *Uncertainties from climate impact modelling:* Development and application of aCCFs presents a major uncertainty of this study. Among others, development of applied functions

[3] Climate mitigation potential is referred to as reduction in ATR20 compared to the reference case in the following.

for North Atlantic region and selected weather situations restricts general validity. Especially contrail effects underlie considerable uncertainties. This is why a more detailed analysis has been performed applying different scaling factors. The results show robustness of climate benefits of flying low and slow for different impact factors of contrails.

In terms of comparability and aggregation of results, taken boundary conditions have to be considered additionally. For this OI, especially selection of representative days and restriction to certain aircraft types is relevant. For further details, please refer to Appendix A.1.

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

The OI focuses on the implementation of the free routing concept with different flight planning strategies while considering wind information. It aims to analyse the mitigation potential of the free routing concept, particularly in high-complexity airspace in which the trajectories can be planned without being constrained by fixed traffic routes. The OI has the potential of reducing travel duration, fuel consumption, CO_2 and non-CO_2 emissions. But, the flight planning strategy has also an impact on the obtained improvements. In this study, we focus on the implementation of the concept using different planning strategies to analyse the mitigation potentials in different cases.

Methodology

A high-complexity en-route airspace (EDUU) in ECAC area is chosen to implement the OI as presented in the previous deliverable, D2.3 [11]. A baseline scenario and three case studies are prepared to analyse the OI. Whereas the baseline scenario corresponds to the reference case in which the aircrafts use their original flight plans, the free routing is implemented with a different planning strategy in each case study. The first case study uses the shortest paths between the entry and exit points in the airspace via the Trajectory Generation Tool (TGT), while the other two case studies utilise the Trajectory Optimization Tool (TOT) to optimise the trajectories according to different predefined objectives. The objective function in Case 2 is the weighted sum of travel duration and fuel consumption, while Case 3 prioritises reducing the non-CO_2 emissions by also aiming to decrease the fuel consumption and travel duration. The simulations are performed for a representative day by using all flight plans obtained from the ALLFT+ data and wind forecasts from the NCEP GFS (National Centers for Environmental Prediction -Global Forecast System) data during the corresponding day. After generating the trajectories via the TGT and TOT for the defined scenarios, a set of KPIs is calculated using the obtained trajectories. In this way, the implementation of the free routing concept in high-complexity airspace and the impacts of the different planning strategies used in this airspace are assessed via a set of KPIs. More detailed information about the methodology can be found in Appendix A.2.

Results

A. Assessment of climate KPIs

The climate KPIs that are evaluated in this OI are CO_2, NO_x, H_2O, and ATR20. The simulation results show that the OI has a high potential to reduce all emission species and ATR20. However, the reduction ratios also depend on the planning strategy. In general, the implementation of the free routing concept in the focused airspace shows a reduction potential of around $7-9\%$ in CO_2 and H_2O, and $26-31\%$ in NO_x and ATR20. The greatest reduction potential for all emission species and ATR20 is observed in Case 3 because the objective function in the wind-optimised trajectory planning in Case 3 prioritises the reduction of non-CO_2 emissions by also considering fuel and time costs. Case 2 uses the weighted sum of the travel duration and fuel consumption as the objective function that results in a reduction of 25.9% in NO_x, 26.2% in ATR20 and 7% in CO_2. A predefined Cost Index (CI) value is selected in Case 2 to create a balance between the time and fuel costs, but the CI in Case 2 can be changed to adjust the relative importance of the travel duration and fuel consumption in the objective function. When compared with Case 2, Case 3 improves CO_2, NO_x, and ATR20 reduction by around 2%, 5%, and 4% respectively, but it affects some of the non-climate KPIs negatively. In addition to them, Case 1 presents the easiest implementation strategy in which the shortest paths are used to define the preferred routes. Although there is no optimization process, this strategy has also an obvious advantage in reducing emissions.

B. Assessment of non-climate KPIs

The non-climate KPIs that are evaluated in this OI are the travel duration, fuel consumption, flight distance, direct operating cost, number of conflicts per flight hour, and ATC complexity score. The KPIs are calculated for each case study to assess the free routing concept and different implementation strategies from the perspectives of the main stakeholders which are airlines, air traffic controllers, and passengers. The simulation results and descriptions of the KPIs are presented in detail in Appendix A.2.

The travel duration, fuel consumption, flight distance, and direct operating cost are used to assess the operational and economic impacts on the airlines. It is observed that the OI has the potential of reducing fuel consumption by at least 7%. The high emission reductions in Case 3 come with a price. It leads to a 3.6% increase in the travel duration. Both Case 2 and Case 3 also lead to a small increase in the flight distance, while Case 1 creates a 1.5% decrease in this KPI. The aircraft fly slower in Case 3 to achieve further improvement in reducing non-CO_2 emissions. Additional direct operating cost arising from the increased travel duration in Case 3 is compensated by the cost reduction in fuel consumption. When compared with Case 2, Case 3 has a 1.5% additional direct operating cost for a further decrease in NO_x by 5.5%, ATR20 by 4%, and CO_2 by 2%.

The number of conflicts per flight hour and ATC complexity score are the main KPIs that are used to assess the safety and ATC workload. It is observed that the OI does not jeopardize safety. All case studies reduce the number of conflicts per flight hour. However, the case studies show different impacts on ATC workload. Case 1 leads to a 22.9% reduction in ATC complexity because of the decrease in the horizontal and vertical interactions originating from using the shortest paths. But, Case 2 shows almost no improvement in reducing the ATC workload, and Case 3 leads to a 21.3% increase in the ATC workload. Because of prioritising the minimization of the NO_x emission, Case 3 generates monotonically decreasing speed profiles that lead to higher potential speed interactions (SDIF). Although the ATC complexity is at a manageable level, the monotonically decreasing speed profiles increase the ATC workload.

The main factors that are used to assess passenger acceptance can be presented as the ticket price and travel duration. We may assume that the ticket price will not increase when the OI is implemented because the direct operating cost is reduced with all planning strategies. However, this study is limited to the direct operating cost. Further assessment should be performed by considering all costs in addition to the direct operating cost to make a clearer conclusion. In terms of the travel duration, Case 3 is the only scenario that leads to an increase. Because the 3.6% increase in the travel duration is not too high, this increase may also be considered acceptable.

C. Discussion on uncertainties

The main uncertainty sources in this OI are presented as initial mass uncertainty, performance model uncertainty, wind uncertainty, emission modelling uncertainty, and climate modelling uncertainty. The initial mass, aircraft performance model, and wind uncertainties have an impact on the flight trajectory, and together they create the flight performance uncertainty. The emission modelling uncertainty and climate modelling uncertainty only have an impact on the emissions and ATR20, respectively. Overall, it is estimated that the flight performance uncertainty has a low impact on the calculated percentage changes. A major uncertainty is presented in the climate impact model (aCCFs) arising from the model development and adjustment process. Further details can be found in Appendix A.2.

2.3 Climate-optimised flight planning

Climate-Optimized Flight Planning (CLIM) aims to identify alternative flight routes that have a lower overall impact on the climate by avoiding regions of the atmosphere that are particularly sensitive to aircraft emissions. This includes both CO_2 and non-CO_2 effects (from NO_x, water vapor, and contrails). Overall, the modelling chain of the climate optimised flight planning relies on the provision of spatially and temporally resolved information on the sensitivity of the atmosphere to aviation emissions to enable trajectory planning and optimisation under climate impact aspects. Considering this climate impact information in the overall objective function (mathematical cost function) of the trajectory optimisation allows us to evaluate and identify alternative trajectories which have a lower climate impact. Results for a winter day in 2018 are presented in this report from a case study in various geographic regions. The day was selected to exploit synergies with other ClimOP OIs.

Methodology

A case study was conducted under the CLIM OI that examined December 11, 2018, and evaluated climate mitigation potential in terms of 20-year average temperature response (ATR20) by avoiding climate-sensitive regions while incurring a fuel penalty from lower than 1% of up to a penalty of 5%. Two aircraft types (B777 and A330) were selected that are representative of the most common aircraft currently in service, and four city pairs (LHR-JFK, FRA-YYZ, SNN-JFK, MAD-SJO) departing from the ECAC area were selected.

Flight time or mitigation potential as well as other KPIs like fuel consumption or ATR20 are calculated via an expanded aircraft trajectory optimisation in numerical simulations (with an expanded objective function comprising climate effects). For this purpose, the Trajectory Optimization Module (TOM) which uses optimal control techniques to determine climate optimised aircraft trajectories, is used similarly to earlier studies in order to determine fuel-optimal trajectories as well as alternative trajectories. Emission quantities are calculated based on Fuel Flow with DLR Fuel Flow method [12]. To compute the ATR20, we use aCCFs (educated guess, BAU) of NO_x, contrails, water vapour and CO_2, similar to the aCCFs used in the FlyATM4E case studies of the year 2018 [13][16]. ECMWF 3-hourly 0.25x0.25° ERA5 reanalysis data were used to calculate these aCCFs. In order to explore the sensitivity of the optimization results to the strength of the non-CO_2 effects in ClimOP, we use a second set of aCCFs to perform a sensitivity study within the range of uncertainties to span the event horizon. For this purpose, we scaled the aCCFs of non-CO_2 effects (NO_x, H_2O, contrails) by an order of magnitude (a factor of 10).

Results

A. Assessment of climate KPIs

When comparing the alternative trajectories to the fuel optimal case, all identified trajectories show a reduction in total climate impact which is equivalent to a mitigation potential. In our pareto analysis of the LHR-JFK city pair (cf. Tables 2 and 3), we identified a climate impact reduction of 2.6% with only a small fuel penalty or 1%, which is equivalent to a mitigation potential of about 0.4 pK/(kg fuel). In contrast to the FRA-YYZ city pair, a considerably larger mitigation potential of 11.4% is identified with a 1% fuel penalty (see table 24 in Appendix A.3), clearly illustrating the strong geographic variation of the mitigation potentials in this OI. For the FRA-YYZ city pair, a fuel increase of about 0.1% reduces the ATR20 already by 4.5%. This is equal to a mitigation potential of about 3.9 pK/(kg fuel). As has been shown, the choice of metric affects the quantitative estimates of mitigation gains. However, the robustness analysis in Matthes et al. 2020 showed that applying different metrics in the given situation leads to alternative trajectories that provide robust mitigation potentials. This robustness analysis could also be performed with the results achieved for these global connections.

Table 2: Changes in major KPIs compared to reference scenario (cost-optimal) for a climate-optimized night flight on December 11th, allowing a fuel penalty of a range from 1% to 5% for a set of climate metrics. For this simulation, CO_2 or non-CO_2 effects have not been scaled.

		Fuel (Penalty) [t]	Flight Time (Penalty) [h]	ATR20 [K] $\times 10^{-9}$	Mitigation potential [pK/ kg fuel]
LHR - JFK	Cost optimal	34.55	7.31	2.70	-
	Climate optimized	+ 1 %	+ 1.2 %	- 2.6 %	- 0.4
		+ 2 %	+ 3.8 %	- 2.6 %	- 0.1
		+ 3 %	+ 5.7 %	- 7.5 %	- 0.2
		+ 5 %	+ 7.2 %	- 10.9 %	- 0.2

When analysing the four city pairs in the sensitivity study “high non-CO_2 effects” aCCF scenario, an almost ten times higher ATR20 value is observed. This was to be expected, as the non-CO_2 effects have the potential to play a dominant role over these short-term time horizon metrics (e.g. ATR20). Our analysis shows that the larger the ATR20 reduction is, the lower the overall mitigation potential. For example, the route from Shannon to New York (SNN-JFK) has a mitigation potential of about 10.1 pK/(kg fuel) when allowing a fuel penalty of 1%. Higher reductions in climate impact would lower the mitigation potential to 5.6 pK/(kg fuel) with a 2% fuel penalty. On the Pareto front, they are located further on the left with a much steeper slope. This is even more pronounced for a flight through the tropical region (Madrid to Alajuela, Costa Rica), where the mitigation optimum is 7.7 pK/(kg fuel) with a 0.6% fuel increase while the mitigation potential is nearly four times lower for the highest ATR20 reduction. These results indicate that for this specific day a flight in the tropical region has a slightly lower overall mitigation potential. On the specific day of the case study, the city pair Shannon-JFK has the higher mitigation potential compared to the other city pairs, e.g. from Madrid or Frankfurt.

Table 3: Changes in major KPIs compared to reference scenario (cost-optimal) for different climate-optimised night flights on December 11th, allowing a fuel penalty of a range from 1% to 5% for a set of climate metrics. For these simulations, the non-CO_2 climate impact were scaled by an order of magnitude (factor 10).

		Fuel (Penalty) [t]	Flight Time (Penalty) [h]	ATR20 [K] × 10^{-9}	Mitigation potential [pK/ Kg Fuel]
LHR - JFK	Cost optimal	34.32	7.16	27.4	-
	Climate optimized	+ 1 %	+ 2.6 %	- 6.5 %	- 3.7
		+ 2 %	+ 4.3 %	- 10.3 %	- 4.4
		+ 3 %	+ 7.3 %	- 16.3 %	- 4.2
		+ 5 %	+ 8.9 %	- 17.1 %	- 3.0

B. Assessment of non-climate KPIs

Avoiding climate-sensitive regions is primarily associated with a slight increase of flight times and potential higher fuel consumption. Nevertheless, small adaptations to the flight path with a low increase in fuel cost and flight time could reduce the climate impact significantly. For a flight from Frankfurt am Main to Toronto, an increase of 0.1% fuel use and 0.1% flight time results in a 4.5% climate impact reduction. For the "high non-CO_2 effects" scenario aCCFs, the flight time penalty does not exceed 2% for three of the city pairs (except Frankfurt), while reducing the ATR20 by more than 5%.

A comparison between the standard case and the sensitivity study with increased non-CO_2 effects shows that there is a small effect on the flight time. In case of increased non-CO_2 effects, the trajectory is optimised mainly on vertical planes, while for the standard case a horizontal correction is more appropriate.

C. Discussion on uncertainties

In addition to uncertainties in weather forecasts and estimates of climate impacts, the choice of climate metric (which allows the climate impacts of non-CO_2 effects to be compared to the impacts of CO_2 emissions) is also a source of uncertainty. The overarching climate goal largely determines the choice of climate metric. Here, we evaluate climate impacts as changes in near-surface temperature averaged over a given number of years or as indicators of this for a strategic change in routing, assuming that such a strategy will not be applied only once but will generally be maintained in the future, corresponding to an emissions scenario. This largely constrains the choice of climate metrics, but some decisions still need to be made, such as the time horizon, e.g., 20, 50, or 100 years, for which the physical climate impacts are analysed. To deal with uncertainties, methods are needed to assess the robustness of an alternative climate-optimized trajectory. With regard to the comparability and aggregation of the results, the boundary conditions met must additionally be considered. In particular, the selection of representative days and the restriction to certain aircraft types are relevant for this OI. For further details, please refer to Appendix A.3.

2.4 Strategic planning: merge/separate flights, optimal network operations

The fleet is the most valuable asset in the airline industry. Efficient operation of the fleet is a crucial decision for airlines to secure their profitability. The operational plan for the fleet should adhere to many internal and external constraints and regulations. This study developed an exhaustive scheduling pipeline to investigate the trade-off between profit and climate impact in three airline types. The contribution is twofold. First, a replanned network is proposed, optimised for both the profit and ATR20. Secondly, an estimated Pareto frontier is calculated in the optimization process which allows a tailored profit vs. ATR20 trade-off. The results are calculated for a representative airline per airline type and extrapolated to all the airlines (of the same type) operating in the ECAC area. Our model suggests a total yearly reduction of 4.2%, 8.6%, and 2.8% in ATR20 and 4.1%, 8.5%, 2.6% in ATR100 for KLM, TAP, and EasyJet respectively.

Methodology

This OI assesses the mitigation potential by optimising the airline network considering ATR20 and profit simultaneously. The primary underlying assumption in this study is modelling the airlines as active decision-makers who try to adapt their operations based on the given facts and figures regarding climate impact and the associated costs of deviating from a business-as-usual state. Three airline types were assessed in this study to incorporate the effects of airlines' business models in their network decisions. Each airline type is modelled by a representative airline. KLM, TAP, and EasyJet are representative airlines for the main hub-and-spoke (H&S), secondary hub-and-spoke, and low-cost carriers (LCC), respectively. The airline selection is based on the geographical scope of their network and the diversity of their routes. The required data of airlines is extracted for 2018 from the Sabre Market Intelligence database [17] per quarter. The itinerary demand and schedule are used to generate the Demand Distribution Function (DDF). To calculate DDFs, we assume a normal distribution of the demand per flight in each Origin-Destination (OD). The summation of all associated normal distributions for each OD will form the DDF for that OD.

The climate KPIs, including ATR20, ATR100, and emissions, are computed for each flight's fuel-optimal trajectory (great circle between origin and destination). The emission and climate impact calculation workflow of the ISOC OI is used to generate data per flight leg for all aircraft types available in each airline fleet. AirClim is applied to calculate the climate response in terms of ATR20 and ATR100 for all non-stop and ISO missions. AirClim is a surrogate model which estimates the ATR20 and ATR100 given a 3D emission profile. A more detailed description of AirClim can be found in [18]. The associated cost of each OD is calculated based on the fuel consumption. An annual airline operating cost report [19] is used to estimate the average fuel cost-share of direct operating costs and the total cost of all flights for all possible fleet types. The results allow Airline Operation Multi-Agent System (AOMAS) to carry out a bi-objective optimization and produce a network plan that incorporates the flights' profit and climate impact.

AOMAS is utilised to calculate the potential reduction in the ATR20 and the induced cost of changing from a profit-optimised network (business-as-usual state) to a climate-optimised network for all representative airlines. The results for each representative airline are extrapolated for all airlines with the same type, proportional to their fleet size. The same calculation is performed per quarter, and the incremental improvement of our bi-objective approach is aggregated. The results illustrate the potential of bi-objective network optimization for the three assumed European airline types operating within the ECAC area in 2018. Further details on the assumptions and modelling process are presented in Appendix A.4.

An integration scenario of the NETW and ISO is also considered to investigate further the climate impact mitigation by implementing ISO and bi-objective network optimization. In this scenario, every OD with more than 2500 nautical miles (NM) distance is assumed to have both options of either fly direct or having an intermediate stop in between. Then, the AOMAS model optimises the network while considering every opportunity to improve the climate impact and profit objective. In this approach, to fly to far away destinations, long haul flights are split into two flights.

Results

A. Assessment of climate KPIs

The new network schedule results show a 4.1 % reduction in ATR20 and 4.2% reduction in ATR100 when the total profit is only allowed to decrease by less than 10 %. AOMAS results sensitivity analysis suggests the profit reduction rate is higher than the ATR20 reduction rate in H&S airlines compared to the LCCs. On the other hand, the potential absolute climate impact mitigation is higher in H&S as more medium to long haul flights are operated by this type of airline. In our case study, reducing frequencies in long-haul routes considering the demand and connection opportunities would mostly impact the ATR20 and ATR100 reduction.

Implementing the strategic network planning OI results in a significant reduction in climate KPIs. For all European airlines with the same types, the extrapolated results suggesting 1.32 mK and 9.69×10^{-1} mK yearly reduction for ATR20 and ATR100, respectively. The relative reduction of all measured climate KPIs are reported in Figure 1. The reported values are from the AOMAS suggested network, which is a single solution in the vast number of the possible solutions when optimising the network incorporating two objectives. To illustrate the relative evolution in the objectives, an estimation of the associated solution evolution diagram is provided for all airline types.

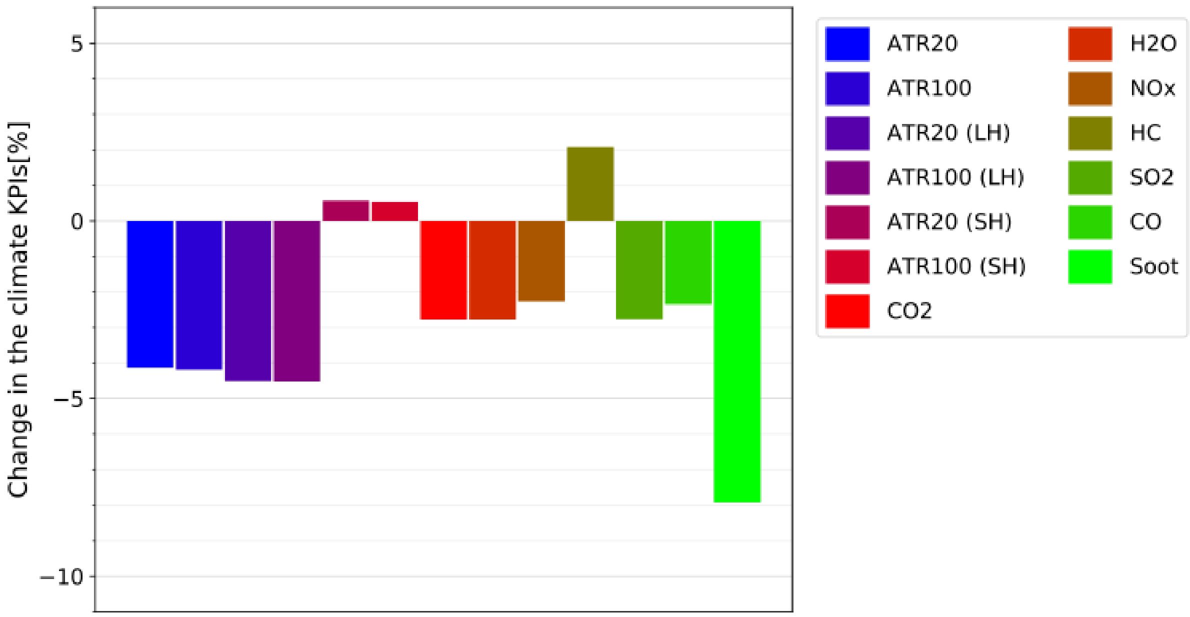

Figure 1. Extrapolated climate KPIs for all airlines within the studied categories in Europe

Analysing the solution evolution diagrams indicates the substantial differences for each representative airline. EasyJet has a slow rate of profit reduction vs. ATR20 reduction in the vicinity of the final solution. This leads to the fact that EasyJet itineraries do not contain any connecting passengers and could be modified independently. On the other hand, diagrams from KLM and TAP are more steeped both on average and in the vicinity of the final AOMAS solution (approximately 1% reduction in ATR20 for 1% reduction in profit) indicates other routes get changed by modifying a single flight. Such a dependence results in a relatively considerable reduction in profit compared with a point-to-point network operation strategy. More details on solution evolution diagrams are presented in the Appendix A.2.

B. Assessment of non-climate KPIs

The reference network and schedule changes are carried out such that the most profitable passenger flow in the network routes remains unaffected. The connecting passengers are extremely important to make their second flight legs profitable, and by changing the inbound flow of connecting passengers to the hub, a snowball effect of outbound frequencies is observed. In KLM and TAP case studies, by reducing the frequency of inbound flights in favour of the ATR20, several outbound flights become unprofitable due to a low load factor or swapping more profitable connecting passengers with local passengers. The route interdependency is much higher in the KLM as nearly 25% of its passengers [20] are connecting passengers. Figure 2 summarises the extrapolated values for non-climate KPIs.

To prevent closing the route in the served ODs by airlines, we have limited the AOMAS to maintain the routes in all ODs unless the network effect of changing the other routes forces the model to stop operating a route. This goal is met with a 1% threshold, which shows the expected routes with no more flights based on the suggested plan. Most of the ATR20 decrease is due to flying on shorter routes rather than medium to long haul flights. Such a change in planning is expected to reduce the number of long-haul flights by 5% to/from the ECAC area, and increase the number of short-haul flights by 0.1%. The total expected ATR20 reduction of 4% will result in a 5% less profit at the airline level. Further investigation of the results and implications of strategic network planning are presented in Appendix A.4.

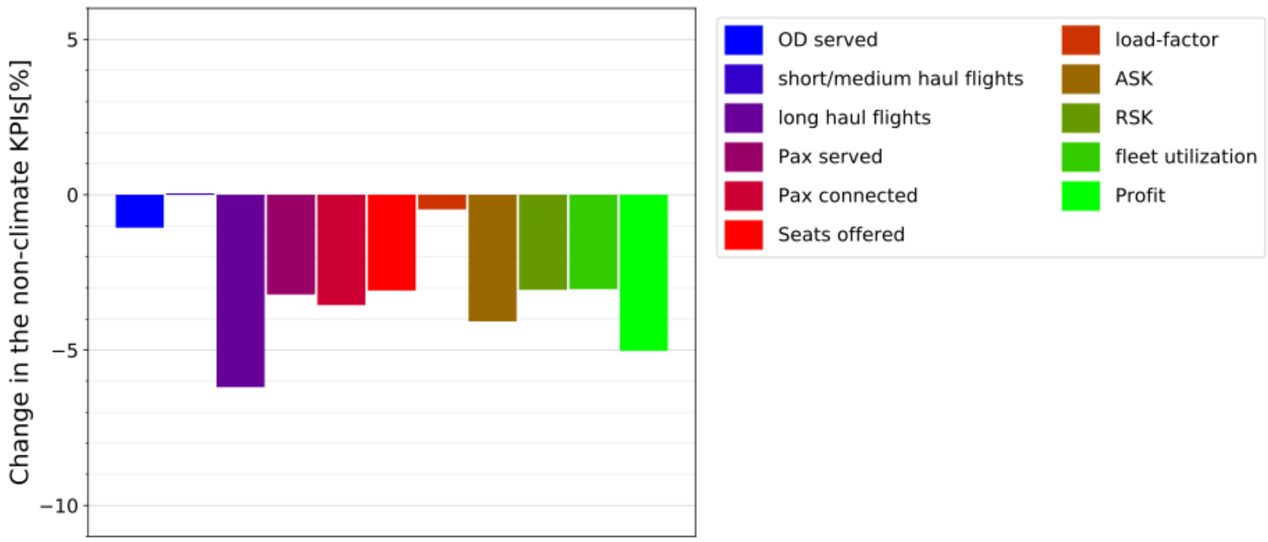

Figure 2. Extrapolated non-climate KPIs for all airlines within the studied categories in Europe

C. Discussion on uncertainties

Strategic network planning aims to prepare a flight timetable to be operated in the coming few months. Interpreting climate impact for such a plan involves uncertainty sources related to the weather condition on the day of operation, modelling the climate impact, and the aircraft performance. Additional assumptions, including flight trajectory, actual load factor, fuel consumption, and flight time, may vary from route to route. We have used numerical models to cover almost all uncertainty sources related to the operation of the aircraft, but the uncertainties related to the climate impact measurements and passenger demand have high volatility in results. In this regard, a more detailed analysis is required to measure the uncertainty bounds to help generate more realistic and accurate results.

2.5 Climate-optimised intermediate stop-over

The effort of burning fuel for carrying fuel can be reduced by intermediate stop operations (ISO). Instead of performing a direct long-haul flight, the mission is interrupted by an intermediate landing for refuelling. Less fuel has to be carried, weight and thus fuel consumption can be reduced. Previous studies [21][22][23] have shown a fuel-saving potential of approximately 5% on a global scale of long-range flights, which is associated with a proportional reduction of CO_2 emissions and the resulting climate impact. By contrast, climate impact from non-CO_2 emissions increases in general. This OI aims to define a climate-optimised implementation of the ISO concept. Thus, the goal is to minimise the climate impact from both CO_2 and non-CO_2 emissions by (1) selecting the intermediate stop airport on climate-related criteria and (2) a limitation of flight altitudes to avoid emission in highly climate-sensitive areas.

Methodology

This study addresses the climate mitigation potential in terms of average temperature response in 20 years (ATR20) and in 100 years (ATR100) by climate-optimised ISO (ISOC) and the effects of an implementation on the Stakeholders of the air transportation system. For this purpose, an annual European long-haul flight plan from 2018 with fuel-optimal trajectories along great circle routes is considered as the reference case (without implementation of the OI). An implementation of the OI is modelled in different configurations. For every mission defined by origin and destination airport as well as aircraft type, a sample of pre-selected intermediate stop airports is considered as well as different levels of cruise flight levels to include emission altitude effects.

In the course of determining climate-KPIs, trip time, fuel consumption, engine and emission quantities per species are modelled along the four-dimension trajectories of every mission with TCM and GRIDLAB. Then, AirClim is applied to calculate the climate response in terms of ATR20 and ATR100 for all non-stop and ISO missions (see [5] for more details on the applied tools). The results allow a comparison between the reference case and a climate-optimised ISO concept as well as a comparison between fuel-optimal and climate-optimal configurations. Also, different acceptable levels of extra fuel and time will be considered. The Stakeholder impact is estimated based on non-climate KPIs, such as fuel consumption and trip time as well as the number of additional starts and landings, which is the basis for an estimation of implementation cost. A survey examines costs and benefits from the passengers' perspective. Further details on the methodology are presented in Appendix A.5.

Results

A. Assessment of climate KPIs

An analysis of the resulting climate KPIs demonstrates a significant mitigation potential of ISOC. Climate-optimised ISO in combination with a limitation of flight levels leads to a reduction in ATR100 of up to 75% on selected individual missions. However, these large potentials do not only result from intermediate stops but also from a reduction of flight levels in comparison to the reference case. In this case, an additional reduction of flight levels is preferable from a climate perspective for the majority of the missions.

An implementation of climate-optimised ISO as a combination of climate-optimal selection of intermediate stop airports and consideration of different flight levels on full European scale implies a climate-mitigation potential of 40.1% in ATR100 (and 38.7% in ATR20). The absolute mitigation potential is 6.93 mK (ATR100) and 10.39 mK (ATR20)[4]. This reduction is mainly due to a reduction in climate impact from contrails and NO_x due to the changed routes, weights and altitudes (Figure 3, right-hand side panel). This overcompensates increasing CO_2 effects (+ 18%) and a general increase in emission quantities caused by longer detours and less fuel-efficient flight levels (Figure 3, left-hand side panel). To decouple the effect of flying lower from sole intermediate stopping benefits in this context, possible reductions in flight altitude can be replaced by a constant flight level (FL350). This case study still shows major mitigation potentials on most of the selected missions (-24% in ATR100 on average). By contrast, though a fuel-optimal implementation of ISO leads to a quantity decrease of most emission species, ATR increases slightly (+ 1%).

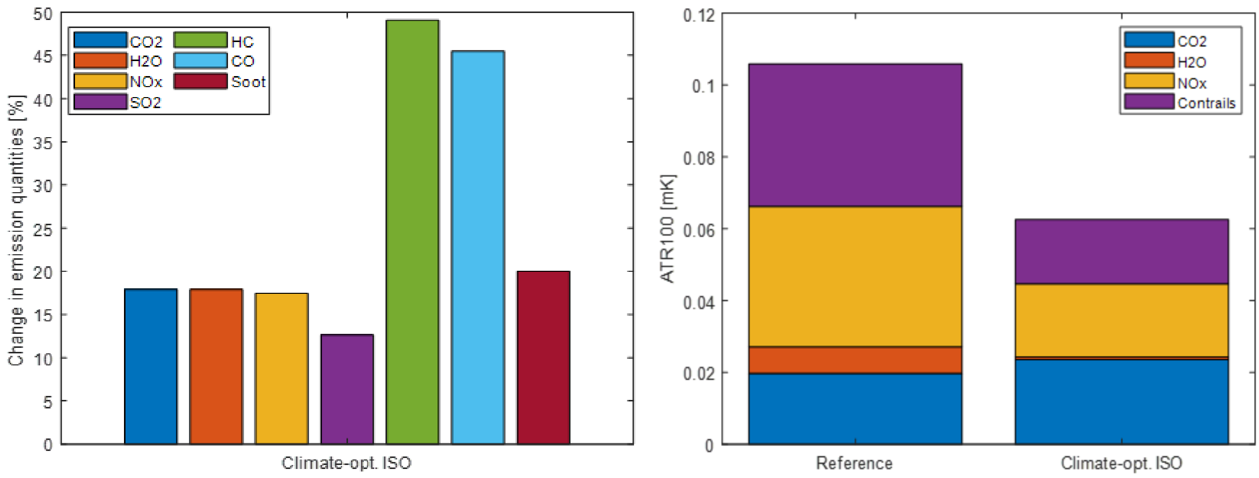

Figure 3. Emission quantity changes and ATR100 of ISOC compared to the non-stop reference case

B. Assessment of non-climate KPIs

Although an implementation of ISOC is beneficial from a climate point of view, this OI is associated with substantial changes in non-climate KPIs. Fuel consumption increases by 18% and trip time by 10% in this context, which limits applicability of this OI from a Stakeholder's point of view. When limiting flight altitude by reducing the flight altitude to a constant cruise level of 35000 ft, changes in fuel consumption (+3%) and flight time (+6%) are moderated. On the other hand, a fuel-optimal implementation increases fuel efficiency by approximately 2%, while trip time is extended by 3% on average in this study, which can be explained by smaller detours in general. The changes in these two KPIs mainly influence the direct operating cost. Furthermore, the number of take-offs and landings increases such that additional fees may occur to the aircraft operators. To limit the efforts associated with ISOC, different limits to extra fuel and time have been applied, and results are presented in Appendix A.5.

Additional take-offs and landings and a shift of flights to more climate-friendly altitudes can further impede an implementation of ISOC as airports and airspaces will experience higher utilisation and possibly congestion.

[4] For the summary of absolute ATR20 and ATR100 we assume a linearization of climate impact, which represents an estimation. Detailed calculations considering saturation effects will be subject to further work following this deliverable.

C. Discussion on uncertainties

When interpreting the climate impact of this OI as well as comparing it with others, uncertainties resulting from the study set-up and the modelling workflow need to be taken into account.

On the one hand, uncertainties evolve from trajectory and emissions modelling, which builds the basis for assessing climate and non-climate effects of this OI. The main uncertainties derive from flight performance assumptions based on BADA4 as well as weight uncertainties, currently assumed with an average European load factor. Also, atmospheric assumptions in terms of International Standard Atmosphere (ISA) and absence of wind have an influence on the achieved results on fuel burn and emissions. All in all, these uncertainties are estimated to have a low impact on fuel flow, flight time and emission quantities and consequently on relative changes in ATR. On the other hand, uncertainties from climate impact modelling and climate impact from different emission species in general have to be considered. Despite these uncertainties, a reliable assessment of the mitigation potential is possible by applying AirClim, where climatological mean of local atmospheric conditions is considered [14]. For further details, please refer to Appendix A.5.

2.6 Single engine taxiing / E-taxi and hybrid

The goal of this assessment is to determine the potential savings of operational towing on a global, European and local level, using Milan Malpensa specifically.

Methodology

First, an analysis is performed to determine the fuel and emissions for four representative aircraft types, the Boeing 737-800 and Airbus A320, both upper medium sized, the Embraer 190 which is lower medium sized, and an Airbus A350, which is heavy sized. By using the average taxi time supplied by Eurocontrol, the average impact for normal taxiing, implementing towing and single engine taxiing for each aircraft type at each airport is calculated for a single peakday in 2018.

For a 2018 peak day, the number of flights per type are multiplied by the savings per aircraft to get the maximum savings for a peak day. This is then converted into annual numbers by assuming an 80% average traffic level compared to the peak day. A yearly estimation is that towing could save 1 billion kg of fuel, and result in a reduction of 3.2 billion kg of CO_2.

While the maximum reduction would be 33.2 tonnes of fuel for the peak day, a reduction of 30 tonnes of fuel could be achieved with 18 tow trucks instead of 34.

Results

Table 4 shows maximum fuel and emission impact of implementing operational towing throughout the European region.

Table 4: Maximum fuel and emission impact of implementing operational towing throughout the European region

	Fuel [kg]	CO_2 [kg]	CO [kg]	HC [kg]	NO_x [kg]	Energy [kWh]
Lower Medium	656,569	2,074,757	15,681	753	3,222	-69,752
Upper medium	2,617,426	8,271,065	92,308	5,305	12,640	-1,573,684
Heavy twins	176,891	558,977	8,558	824	757	-129,476
Total Peak day	3,450,886	10,904,799	116,548	6,882	16,618	-1,772,912
Year estimate	1,007,658,611	3,184,201,297	34,031,909	2,009,649	4,852,360	-517,690,274
Saving	75%	75%	85%	85%	85%	

Table 5 illustrates that for Malpensa, most of the fuel and emissions savings with less costs, by using fewer tow trucks. This trade-off is illustrated in Figure 4.

Table 5: Malpensa fuel emissions

	Tow trucks	Fuel [kg]	CO_2 [kg]	CO [kg]	HC [kg]	NO_x [kg]
Maximum savings	34	33191	104883	1181	71	166
Balanced	18	29830	94262	1043	61	150

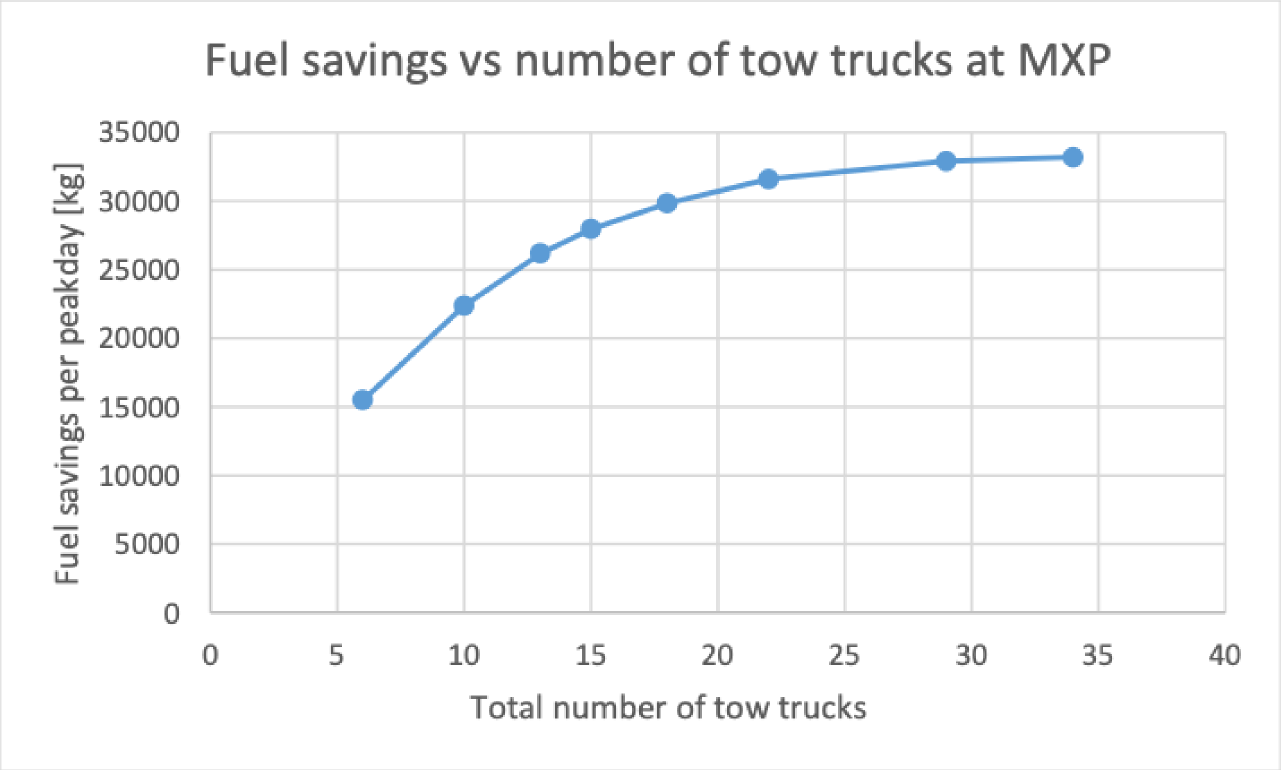

Figure 4: Fuel savings vs. number of tow trucks at MXP per (peak) day.

To keep staff requirements low, ideally the towing solution should be autonomous and not required an (additional) driver.

Towing is expected to have a slight impact on taxi time, but estimation of this impact is not currently within the scope of the present assessment as it would require detailed simulations. For more detailed simulations, we refer to the AEON project.

The main uncertainties are the price of the trucks, the price of fuel, the time needed between towing operations and the time needed to warm up and cool down the aircraft engines before take-off and after landing. The warm up and cool down time need to be monitored by the airline. The others need to be continuously monitored and updated in the analysis when they are implemented by the airport.

For eTaxi, as there is no definite design and knowledge of total installation weight, initially it is assumed that the system would add 500 kg to narrowbody aircraft.

Results show that significant savings are possible on a narrowbody (Boeing 737 and Airbus A320) fleet as illustrated in Figure 5. However, the business case is very dependent on the fuel savings per day required to compensate for the installation costs. Additionally, Table 6 illustrates the impact of the marginal cost, the amount of fuel an aircraft must save within a day to repay for the installation, for Easyjet. NO_x emissions actually increase due to the increased fuel burn in flight.

Installing eTaxi on only a few aircraft, which, then, specialise in the shorter-range flights between airports with longer taxi times, can significantly increase the savings per aircraft and thus the business case. However, these airports with long taxi times are also very likely airports that would implement operational towing.

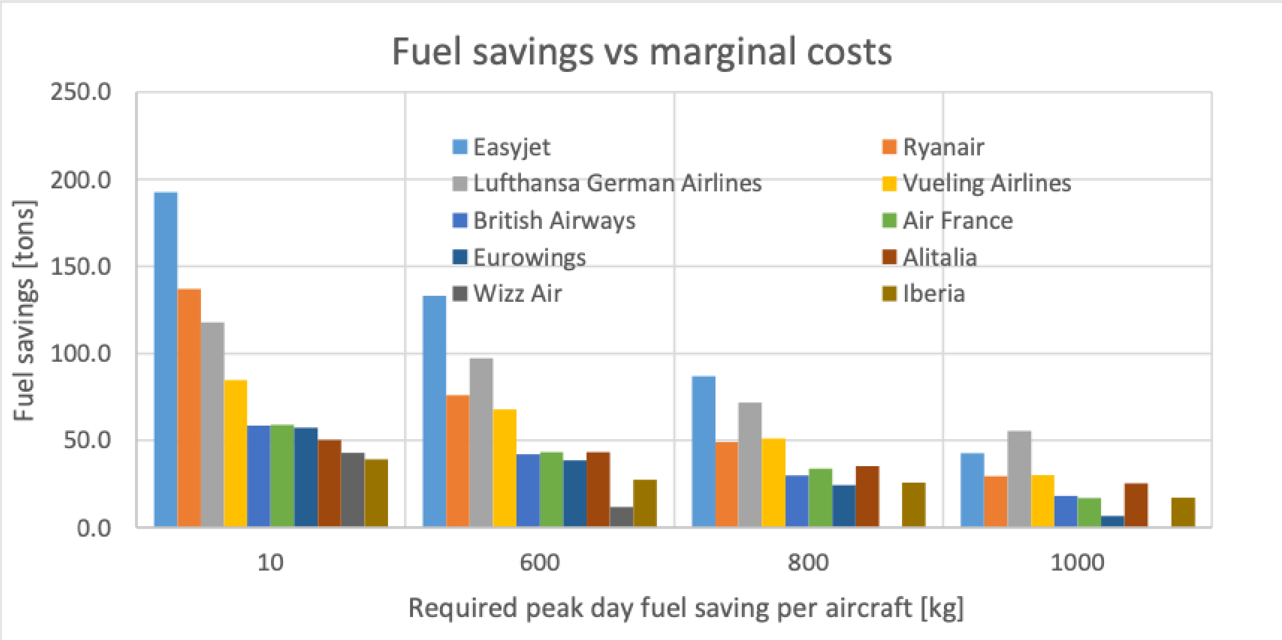

Figure 5: Fuel savings for some airlines B737 and A320 fleets per (peak) day.

Table 6: Fuel and emissions impact of eTaxi installation for Easyjet per (peak) day.

Required fuel saving per aircraft [kg]	Number of aircraft equipped	Fuel [tons]	Savings per aircraft [kg]	CO_2 [tons]	CO [g]	HC [g]	NO_x [kg]
10	338	-192.7	570	-608.9	-2977	238.6	642.9
1000	36	-42.6	1183	-134.6	-1144	-19.4	72.0

2.7 Electrification of ground vehicles and operations

In the context of reducing the overall emissions of the aviation industry, we want to evaluate the impact of the Ground Support Equipment and Operations. To achieve this, we model the fuel consumption of the present fossil-fuel-powered fleet, and we compute the corresponding CO_2 emissions, which constitute the largest proportion of GHGs emitted at ground level. Subsequently, we compare this result with the emissions of a corresponding electric-vehicle-only fleet. As a first step, we develop a model which uses ground fleet data from the SEA Milan Airports MXP and LIN, and we implement a tool to visualise the results. We, then, propose a method to generalise our results to any airport in the EU, and for the EU as a whole. We refer to the ground scenario (cf. Sect. 2.9 and A.9) for the expanded analysis that includes other GHG emissions, e.g. CO, NO_X and particulate matter, which have a lesser impact on climate but significantly contribute to the local air quality on the airport ground.

Methodology

The scope of the electrification of ground operations is twofold. Firstly, we want to calculate a prediction of the GHG emissions and the temperature response of electrifying the ground operations fleet at any single airport in the ECAC area in the next 20 and 100 years. Secondly, we aim to estimate these same results for every airport in the ECAC area as a whole.

The key hypothesis is that electrifying the ground operations fleet will have a long-term positive impact on climate due to the difference in GHG emissions between the burning of fuels in traditional diesel and petrol vehicles, and the GHG emissions produced from generating the required energy to power an electric equivalent fleet for the same intensity of operations. It is expected that this lower amount of emissions will reduce the impact on the Earth temperature in a way that makes the electrification of ground operations worth the investment.

The data used is provided by SEA. It encompasses the ground operations vehicles in LIN and MXP airports during all of 2018, which is the temporal scope adopted in most OIs. As the original dataset also includes 2019 data, the study can in principle be extended. For each airport several fields are used in the categorisation and processing of each vehicle.

Table 7. Vehicle categorisation.

Field	Description
Model	The make and model of each vehicle present in the fleet.
Airport	The airport in which the vehicle operates.
Fuel type	Fuel type used by the vehicle. Diesel, petrol or electric.
Vehicle type	4x4, van, minivan, bus, etc.
Days of use	Yearly days in which the vehicle is used
Use per day	The number of kilometres the vehicle is used for in a day.

Results

A. Assessment of climate KPIs

Results show that the electrification of ground operations does indeed reduce the emissions due to airport operations. The energy required to power an electric fleet of 1000 vehicles produces lower GHG emissions than those emitted by traditional vehicles by 4028 tons, a factor of 84.1% improvement. This is reflected equally in the temperature response, with a drop of 1.68×10^{-8} K in 20 years and 1.87×10^{-7} K in 100 years, a factor of 84.1% improvement. Table 36 in Sect. A.7 summarises the main results of this analysis.

B. Assessment of non-climate KPIs

The non-climate KPIs show a high initial cost with savings in the long term. The purchase of electric equivalent vehicles to replace the fleet is costly. Replacing a fleet of 1000 vehicles is estimated at 208.44 M€. The savings come from the cost of fuel versus energy, and the maintenance costs of the vehicles. The estimated yearly fuel to energy savings for the same fleet is 3.35 M€, and the Estimated Yearly Maintenance Savings is 130.44 k€, showing a period of 60 years for return of investment. Table 38 and 39 in appendix A.7 give an overview of the purchase and maintenance costs estimated for the complete transition to a fully-electric ground fleet.

C. Discussion on uncertainties

Due to the scaling nature of the OI, many uncertainties are aggregated along the calculation process from assumptions and generalisations. They are mainly:

- Averaging fuel consumption of synthetic fleets of small, medium, large vehicles based on average mileage.
- Averaging energy demand of synthetic electric fleet of small, medium, large vehicles based on average mileage.
- Distribution of vehicles in airports other than MXP and LIN.
- Electric equivalent of existing fossil-based vehicles.
- Fuel to GHG conversion factors.
- GHG emission factors for energy generation.
- Conversion of emissions to ATR.

2.8 Upgrade of the airport infrastructure according to energy efficient criteria

Airport buildings consume a significant amount of energy to maintain comfortable occupancy conditions, which require space heating and domestic hot water preparation, ventilation and air conditioning/cooling, power supply for lighting and other airport systems (e.g., elevator.). The improvements in the infrastructure according to energy-efficient criteria are expected to significantly reduce the energy consumption of airports, and hence their GHG emissions. This assessment clarifies the effectiveness of the OI in reducing airport impact on climate, the operational and economic impact on the key stakeholders, and how it is perceived by them.

Methodology

The assessment of this OI focuses on the analysis of the change in CO_2 emissions thanks to the application of a selection of energy-efficiency measures to the office buildings of European airports. The analysed energy-efficiency measures include (i) insulation of exterior walls, (ii) optimization of windows, and (iii) introduction of LED lights.

The assessment strategy entails five steps.

1. Each EU airport is associated with one of the 4 most common climate zones by following the ASHRAE classification of geographical distribution of climate conditions [24].
2. For each climate zone, we simulate the energy consumption of a conceptual office building by using EnergyPlus, the open-source software developed by the US Department of Energy.
3. We scale the results to the total energy consumption for each airport with a proxy calculated as a logarithmic function of the number of aircraft movements.
4. The CO_2 emission resulting from the energy consumption is estimated.

5. The procedure is repeated for future climate conditions. The EnergyPlus model includes a module for future-climate simulations, that is based on climate conditions representative of 2050. We linearly interpolate in time the values of CO_2 emissions for 2019 (present-day) and 2050 (future) to calculate the Average Temperature Response (ATR) over 20 and 100 years.

Results

A. Assessment of climate KPIs

In the first step, the study focuses on the climate-impact of the present OI. The reduction of energy consumption, and consequently CO_2 emissions, ranges between 20 and 30%. The corresponding results for ATR20 and ATR100 are reported in Table 8. Both ATR20 and ATR100 are reduced by about 20%. More specifically, ATR20 is reduced from 1.66 μK to 1.31 μK, and ATR100 from 8.90 μK to 6.30 μK. The results only loosely depend on future climate conditions, hence the positive effect of the OI is consistently demonstrated for all the considered socio-economic development scenarios (see details in A.8).

Table 8. Values of ATR20 and ATR100 for business as usual and after the implementation of the OI. The difference between the two is also reported in percentage. The results show the average among different socio-economic scenarios as defined for future climate projections of the CMIP initiative.

	BAU (10^{-6} K)	OI (10^{-6} K)	Δ (%)
ATR20	1.67	1.31	21.68
ATR100	8.09	6.30	21.92

B. Assessment of non-climate KPIs

In the second step, we aim to assess the impact on the key stakeholders through selected non-climate KPIs. To assess the economic impact, a Cost-Benefit Analysis (CBA) has been performed. The benefit of implementing the energy efficiency measures is the reduction of the expenses for energy consumption. The initial investment has been estimated on the basis of reference unitary costs and the characteristics of the conceptual office building used in this study. The CBA for the conceptual office building is, then, scaled at airport level by using the same approach defined previously. Malpensa and Linate airports have been considered as reference cases. The time to return on investment is about 50 years.

Besides the economic assessment, we investigate the social acceptance of this OI thanks to the ClimOP survey. The survey showed that the majority of passengers is in favour of travelling to and from climate-neutral airports (see Appendix C). Furthermore, discussions carried out during the advisory board meetings and an extra workshop with 11 European airports highlighted that the market acceptance of this OI is relatively high, despite the large initial investment. The OI is also politically well received, as some late policies and regulations concerning energy efficiency aspects suggest (e.g. 2. ICAO's Policies on Charges for Airports and Air Navigation Services (Doc 9082)).

C. Discussion on uncertainties

It is worth mentioning that our calculation entails a wide range of uncertainties. The exploited method includes some key assumptions.

a. A conceptual office building is used to assess the energy demand of any airport office building throughout Europe. This simplification is necessary to reduce the complexity and generalise the results. However, it results in an uncertainty of about 20%.
b. Parallel to this, we also standardise the energy efficiency measures, although they generally depend on the regulations of each Country. Such a work hypothesis results in an uncertainty of about 5%.
c. The results are then scaled through a logarithmic function of the number of flight movements. The logarithmic fit has an error of about 40%, and the overall approach leads to an uncertainty of 30%.
d. The energy consumption is converted into CO_2 emissions, based on the assumption of total utilisation of electric energy. Such an assumption results in 5% of uncertainty. Finally, the conversion factors have their own uncertainties, estimated to be about 10%.

Despite the uncertainties in the results, the assessment shows the climate impact of the OI is rather relevant. It has been shown that it has a positive response from all the key stakeholders. Finally, from an economic point of view, it has advantages over the long term, which make it appealing despite the conspicuous initial investment.

2.9 Ground-operation-related scenario

The "ground scenario" studies the combined impact of the three OIs related to enhancing the sustainability of ground operations, equipment, and infrastructure. In particular, the OIs considered in the ground scenario are electric towing, the electrification of GSE and ground-handling operations, and the upgrade of the airport infrastructure, specifically the office buildings, according to energy efficiency criteria. The goal of this scenario is twofold. At a research level, it aims at describing a methodology for comparing the impacts on climate of different operational concepts, using the ground OIs as a case study. At a higher level, the purpose is to provide a harmonised view of the cumulative reduction of GHG emissions that is achievable by deploying all three OIs, and their integrated impact in terms of climate-change mitigation.

Methodology

The goal of the assessment is to model the combined impact on climate of the three ground OIs. This impact is evaluated in terms of a list of KPIs shown in Table 9. The basic working assumption in the ground scenario is that the three OIs can be implemented independently, and their total impact is the sum of the contributions of each individual OI. However, because the modelling methodologies adopted in the three OIs differ substantially, a strategy was devised to harmonise the results to make their comparison possible, as described in detail in Sect. A.11. To combine these OIs, the ground scenario focuses on two case studies, for both of which the reference year is 2018:

a. A "high-resolution" analysis of the ground operations and infrastructure of MXP airport. This case study builds on the detailed data shared within the ClimOP consortium by the SEA Milan partners. This data includes taxi-in and taxi-out times for a representative selection of narrow-body and wide-body aircraft types (cf. Sect. A.6), the composition of the ground fleet and average daily mileage of each vehicle, and the energy consumption of different areas of the Malpensa Airport.
b. A "low-resolution" analysis of the cumulative impact of all airports at the ECAC level, which is a parametric generalisation of the results of case study (a). The approach to scale up is to

use the number of flight operations as a proxy for the size of the airport and thus for its consumption of fuel and energy and GHG emissions. In the case of the ground fleet, the relationship between the number of yearly flight operations and that of ground vehicles is assumed to be linear (cf. Sect. A.7). The energy consumption of office buildings is assumed to scale logarithmically with number of yearly flight operations (cf. Sect. A.8). The limitations of this approach are summarised in Sect. A.11.3. Because different airports have very different taxiing times, the alternative approach to estimate the overall impact of taxiing operations is to consider the average taxiing times at the ten busiest airports in Europe[5], and an A320 as a representative aircraft type to calculate the average fuel consumption.

For both case studies, the model predicts the total amount of fuel and energy consumption in a business-as-usual case and in a scenario where all OIs are deployed. From this, the emissions of different GHG are calculated through the conversion factors for different pollutants available in the literature [25] [26].

Results

A summary of the results for the ground scenario is presented in Table 9. The detailed assessment against each KPI for the individual OIs is shown in Table 60 in the Appendix A.9. The reduction of the contribution to global warming is evaluated in terms of difference in the average temperature response at 20 and 100 years (ΔATR20 and ΔATR100, respectively). For a mid-size airport such as MXP, ΔATR20=-0.14 μK and ΔATR100=-1.6 μK. Extrapolating these results to the ECAC area, it is found that ΔATR20=-11 μK and ΔATR100=-120 μK. Almost 90% of the emissions related with ground operations and infrastructure come from the taxiing operations (cf. Table 60). Approximately two-thirds of the remaining emissions are related with the generation of energy necessary for the heating, cooling, and illumination of the airport office buildings, and one-third for the GSE and ground handling operations. The greatest emission reduction, a factor of about 6, can be achieved by electrifying this latter component. Electric towing has the potential to approximately halve the emissions from taxiing, whereas enhancing the energy efficiency of the buildings can reduce the yearly energy consumption, and thus the related emissions, by 20%.

The sources of uncertainty of the ground scenario are the same discussed for the individual OIs. These include the limited number of vehicles and aircraft that are considered in the quantification of the emissions from taxiing and the ground fleet, the energy consumption of the replacement vehicles, and generalisation method to extrapolate the results obtained for the Milan airports to the entire ECAC area. This generalisation does not allow to differentiate between seasonal and non-seasonal airports in terms of traffic flows and consequently the handling equipment necessary to sustain this traffic, and to capture the infrastructural characteristics of different airports.

The main limitations to the feasibility of this scenario are economic and operational. The three OIs are based on relatively mature technology, but large investments are necessary for their deployment as they require multiple changes to the airport infrastructure. These include for example to create specific areas for coupling and decoupling the tugs for electric towing, charging stations for all electric vehicles and equipment, and so on. In conclusion, this suggests that the implementation of the ground scenario, while technically feasible, will require a strong support from public entities to make it sustainable and thus encourage the stakeholders to contribute to the transition.

[5] Average taxiing time at the main EU airports are available on Eurocontrol's website. Those referenced in this context can be found at https://www.eurocontrol.int/publication/taxi-times-summer-2018 and https://www.eurocontrol.int/publication/taxi-times-winter-2018-2019.

Table 9. Summary of the Ground scenario results. The cumulative impact of the OI deployment is compared to business as usual and evaluated against a set of KPIs for the detailed MXP and the generalised ECAC case studies, respectively.

KPI	MXP case study		ECAC case study	
	BAU	With OIs	BAU	With OIs
CO_2 Emissions (tons/year)	6.81E+04	3.23E+04	5.36E+06	2.67E+06
CO Emissions (tons/year)	5.82E+02	2.05E+02	4.11E+04	1.43E+04
NO_X Emissions (tons/year)	8.34E+01	3.01E+01	5.85E+03	2.07E+03
$PM_{2.5}$ Emissions (tons/year)	1.41E+01	4.98E+00	9.97E+02	3.48E+02
PM_{10} Emissions (tons/year)	1.77E+01	6.23E+00	1.25E+03	4.35E+02
ATR20 (K)	2.70E-07	1.30E-07	2.04E-05	9.32E-06
ATR100 (K)	2.96E-06	1.36E-06	2.16E-04	9.56E-05
Fuel consumption (litres/year)	2.43E+07	1.09E+07	1.71E+09	7.48E+08
Energy consumption (kWh/year)	2.60E+04	6.98E+06	4.66E+06	5.16E+08

3. Discussion on effectiveness and applicability of the OIs

One of the ambitions of ClimOP is to harmonise the OI assessments such that they can be compared to design the most effective mitigation strategy in WP3. However, the assessment strategies used by the different working groups depend on the specific characteristics of the OI as well as on the adopted models. Before discussing whether and how the OI assessments can be compared, it is worth analysing how much the basic assumptions differ among studies, and what is the share of the total OI effect that is actually covered based on such assumptions. A comprehensive overview of all the analysed OIs is presented, followed by a strategy to harmonise the OI assessment for future work in WP3. Subsequently, the applicability of the OIs is examined considering the impact of the stakeholders measured by the non-climate KPIs. Such analysis builds on the work reported in the Appendices B, C and D. Finally, a qualitative comparison including both climate and non-climate KPIs is presented.

3.1 Assumptions and analysed share used by the OI assessments

In the present section, we present an overview of the basic assumptions, divided into seven categories:

- *Temporal scope*: to limit the computation resources needed, the analysis might be limited to a portion of time selected according to specific assumptions such that the results are representative of a longer period of time;
- *Geographical scope*: similarly to the temporal scope, the geographic scope might be limited to a portion of the European airspace;

- *Aircraft fleet*: the studies might consider only selected types of aircraft, as they are the most relevant for the specific OI;
- *Flightplan*: all or a subsample of the aircraft operating in the specific time windows and airspace are considered;
- *Airport selection*: some OIs are linked to the operations at, from and to specific airports, and hence a selection of airports needs to be made;
- *Airspace selection*: similarly to the airport selection, specific airspaces might be considered in the different studies;
- *Airline selection*: similarly to the airspace selection, specific airlines might be considered in the different studies.

Starting from the basic assumptions, we estimate the share of the total OI effect that is actually covered by the analysis. The information is collected in Table 10, 11 and 12, corresponding to the three categories of OIs, namely trajectory-related, network-related and ground-related OIs, respectively.

Table 10. Assumptions and share of the total OI effect for the OIs belonging to the trajectory-related category.

Trajectory-related OIs		
Category	**Description**	**Share covered [%]**
Flying low and slow		
Temporal scope	4 selected days of 2018 (based on DWD classification)	4/365 = 1.1%
Geographical scope	All flight from/to ECAC on that day, no restrictions	100%
Aircraft Fleet	Selected aircraft: B777 & A330, A320 & B737	36 % ASK per day
Flightplan	Limited by aircraft type + date (see above)	100%
Airport selection	No additional restrictions	N/A
Airspace selection	No additional restrictions	N/A
Airline selection	No additional restrictions	N/A
Free routing and wind-optimised flight planning in high-complexity airspace		
Temporal scope	1 selected day of 2018 (one of the selected days in LOSL is used to improve comparability - December 11th)	1/365 = 0.27%
Geographical scope	A high-density en-route airspace (EDUU) in ECAC area (4 en-route sectors are aggregated - EDUU west, east, north, and south)	17% of all flights operating in ECAC area use this airspace
Aircraft Fleet	Selected aircraft: B737-800	16.7% of aircraft operating in the corresponding airspace are B737-800.

Flightplan	Flight plans of all aircraft operating in the airspace (Representative aircraft is used to scale to full fleet)	100%
Airport selection	N/A	N/A
Airspace selection	A high-density en-route airspace (EDUU) in ECAC area	17% of all flights operating in ECAC area use this airspace
Airline selection	No additional restrictions	N/A
Climate-optimised flight planning		
Temporal scope	4 selected days of 2018 (based on DWD classification/NAFC REACT4C) Occurrence of archetypical weather patterns in NAFC	4/365 = 1.1% (simple estimate) Classification probability
Geographical scope	NAFC (Traffic sample includes all flights from/to ECAC on that day, no restrictions)	
Aircraft Fleet	Selected aircrafts: B777 & A330, A320 & B737	36 % ASK per day
Flightplan	Limited by aircraft type + date (see above)	100%
Airport selection	No additional restrictions	N/A
Airspace selection	No additional restrictions	N/A
Airline selection	No additional restrictions	N/A

Table 11. Same as table 8 but for the network-related category.

Network-related OIs		
Category	**Description**	**Share covered [%]**
Strategic planning: merge/separate flights, optimal network operations		
Temporal scope	Full year 2018 (aggregated flight plan)	100%
Geographical scope	All airline flight from/to ECAC area	100%
Aircraft Fleet	Available aircraft in the representative airlines' fleet	283 bn ASK = 0.01%
Flightplan	both short and long-haul flights based on the representative airline schedule in 2018	
Airport selection	preselected airports based on the operation of the representative airlines in the 2018	N/A
Airspace selection	N/A	N/A
Airline selection	Main hub and spoke, secondary hub and spoke and low-cost carriers	Three representative airlines from each category which in total have 0.01% of total airline flights within/to/from the ECAC area

Climate-optimised intermediate stop-over		
Temporal scope	Full year 2018 (aggregated flight plan)	100%
Geographical scope	All flights from/to ECAC area	100%
Aircraft Fleet	Selected aircraft: A330, A340, A350, A380, B747, B767, B777, B787	1,794 bn ASK = 53.4%
Flightplan	Only long-range flights (> 2,500 NM)	
Airport selection	Preselection for ISO airport based on offset, detour and AirClim resolution	N/A
Airspace selection	N/A	N/A
Airline selection	N/A	N/A

Table 12. Same as table 8 but for the ground-related category.

Ground-related OIs		
Category	**Description**	**Share covered [%]**
Single engine taxiing / E-taxi and hybrid		
Temporal scope	4 days in 2018 representing high and low demand days in Summer and Winter operations	1.10%
Geographical scope	All flights to/from selected European airports on 4 representative days of operation	100%
Aircraft Fleet	Narrow body: A318 to A321, B737 to B757 Widebody: A330 to A380, B767 to B747	TBD
Flightplan	No additional restrictions, limited only by aircraft type	N/A
Airport selection	10 busiest in Europe in 2018 based on number of aircraft movements	TBD
Airspace selection	No additional restrictions	N/A
Airline selection	No additional restrictions, limited only by aircraft type	N/A
Electrification of ground vehicles and operations		
Temporal scope	2018	100%
Geographical scope	Milan MXP + LIN	3%
Aircraft Fleet	N/A	N/A
Flightplan	N/A	N/A
Airport selection	Milan MXP + LIN	3%
Airspace selection	N/A	N/A
Airline selection	N/A	N/A

Upgrade of the airport infrastructure according to energy efficient criteria		
Temporal scope	2018	100%
Geographical scope	Europe	100%
Aircraft Fleet	N/A	N/A
Flightplan	N/A	N/A
Airport selection	674 in Europe	100%
Airspace selection	N/A	N/A
Airline selection	N/A	N/A

The OIs belonging to the same category share several common denominators. All trajectory-related OIs were assessed on the 11th of December 2018. Both *Flying low and slow* and *Climate-optimised flight planning* are evaluated for all the flights from and to ECAC, whereas *Free routing and wind-optimised flight planning in high-complexity airspace* has been studied in a sub-sample of this airspace, i.e. EDUU. Concerning the network-related OIs, the analysis has been performed for the whole 2018 and all the flights from and to the ECAC airspace. The considered aircrafts are the ones performing long haul flights. Although *Strategic planning: merge/separate flights, optimal network operations* focuses on specific airlines, the results can be upscaled to the full European airspace (see Appendix A.4 for details). Finally, the ground-related OIs share a common starting point, i.e., the case study of Malpensa airport. The working groups responsible for the different ground-related OIs defined different approaches to generalise the results such that they are representative of the whole Europe. From a temporal point of view, they performed the analysis in 2018, with *Single engine taxiing / E-taxi and hybrid* focusing on four days representing high and low traffic conditions in summer and winter.

All the OI assessments include the estimate of ATR20. However, different assumptions are used for the different categories. The trajectory-related OIs used the aCCF technique to calculate ATR20 [13]. The aCCF technique calculates the instantaneous climate impact for each species individually (including CO_2, ozone, methane, water vapour and contrail induced cirrus clouds). The instantaneous climate is, then, aggregated along the trajectories to obtain the total climate impact. This choice is motivated by the relevance of contrail and induced cirrus formation for the estimate of the mitigation potential of these OIs. On the other hand, the network-related OIs employed AirClim [18] for the ATR20 calculation. Since the focus of these OIs is not on specific weather phenomena, the climate impact is adequately estimated using a climate-chemistry response model such as AirClim. Based on the representative weather situations, climatological mean flight patterns could be derived and evaluated with AirClim on a climatological basis. Using the technical terminology, AirClim calculates F-ATR (future emission scenario-based ATR) whereas aCCF results are P-ATR20 (ATR from pulse emission), where F-ATR is typically significantly higher than P-ATR (i.e. around one order of magnitude). Finally, the ground-related OIs exploited the formulation of Sausen and Schuman 2000 [27] for the calculation of ATR20. This approach is based on the assumption that the perturbations of the radiation forgings are small enough to use a linear approximation of their effect.

In conclusion, the OI assessments are more accurately comparable within their own categories. The assumptions within the three OI categories have been aligned in the definition process, so that a semi-quantitative approach can be deployed to enable a first comprehensive overview of the outcomes within the categories. In particular, the ground-related OIs have been studied following a common approach that started from a high-resolution case study, corresponding to Malpensa Milan airport, to be then generalised for the whole Europe. Thanks also to the activities for the assessment of the ground scenario, the harmonisation of these OI assessments has reached a significant level (see Appendix A.10). Similar considerations apply to the trajectory-related and network-related OIs.

3.2 Comprehensive overview of the climate-impact assessments

A preliminary comprehensive overview of the OI assessments, within each category, is provided in Figure 6. The results are displayed as a bar chart. The bars correspond to the mitigation potential, which is the difference in ATR20 value of the BaU and with the OI implemented cases, normalized by the value of ATR20 of the BaU case. Above the bars, the absolute values are provided for completeness. It is worth stressing that the overview needs to be interpreted in light of the assumptions presented in the previous section and in particular of the total share of operations covered by the analysis, where the share indicates the percentage of operations analysed in the assessment (see Table 8, 9, and 10). The Figure includes three panels, each of them corresponding to an OI category.

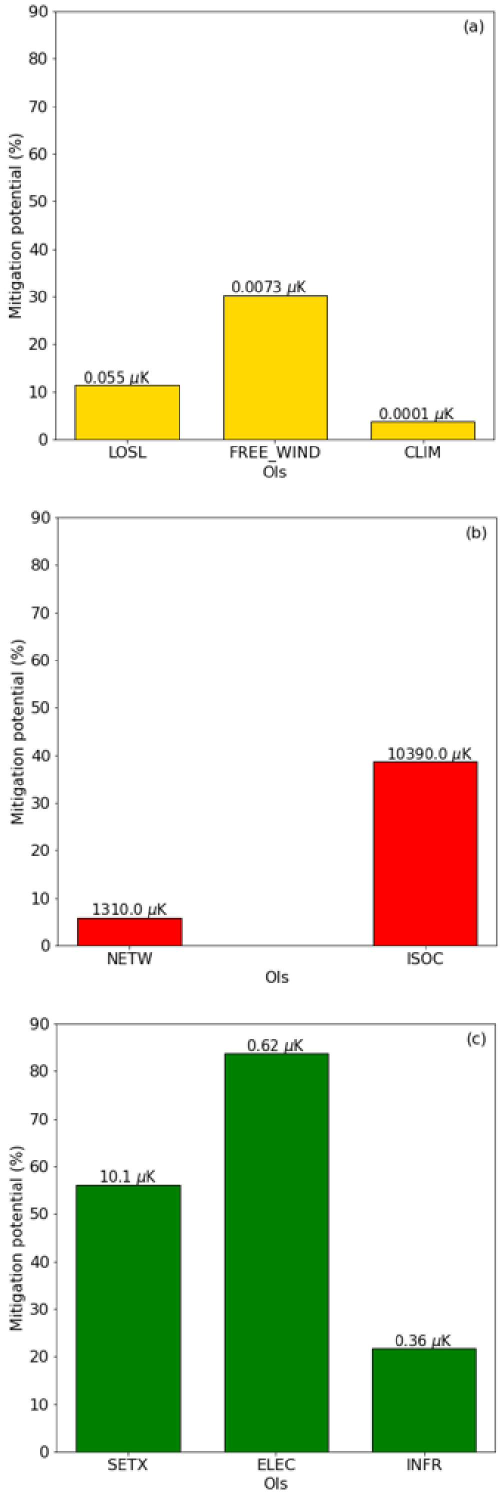

Figure 6. Comprehensive overview of the OI assessments separated by OI category. The bars indicate the relative mitigation potential, while the absolute values are given above. (a) Trajectory-related OIs, where the mitigation potential is calculated on the basis of the pulse-ATR20, (b) network-related OIs, where the mitigation potential is calculated on the basis of the sustained ATR20, (c) ground-related OIs, where the mitigation potential is calculated on the basis of the formula by Sausen & Schumann [27].

Some of the OIs are studied through the definition of different case studies. In that case, the highest mitigation improvement has been considered. An exception is *Climate-optimized flight planning*, which is depicted for the case with a fuel penalty equal to 1%. The reason for this choice is the decision to stress the effectiveness of this OI even with a limited increase in fuel for the airlines.

The visualisation in Figure 6 was designed to highlight the relative mitigation potential. However, this information is not sufficient to have a complete idea of the effect of the studied OIs. In fact, there is not direct relationship between these values and the absolute mitigation potentials. A clear example is panel (c) in Figure 6, where *Electrification of ground vehicles and operations* has notably a higher relative mitigation potential but is not as striking when looking at the absolute values. It is worth stressing that a comparison of OIs belonging to different categories is even more complicated. This is due to the different assumptions used in the assessments as well as the different way to calculate ATR20. Just to give an idea, the mitigation potential as calculated for the trajectory related OIs (based on the pulse-ATR20) might be one order of magnitude lower than the one of the network related ones (based on the sustained-ATR20). The difference with the method used for the ground-based OI has not been estimated. However, this comprehensive overview lay the foundation for the work to be carried out in WP3 aimed at using the climate-related KPIs to identify the most effective OIs. To make a step forward in this direction, the next section suggests a strategy to harmonise all the in-flight OIs.

3.3 Strategy to harmonise the in-flight OIs

In the context of comparing the climate mitigation potential of the different OIs, boundary conditions as well as different scopes of the studies need to be considered. A direct comparison of OIs of different categories (trajectory-related, network-related, and ground-related) is limited due to the different assumptions and applied models. While the trajectory-related OIs apply algorithmic climate-change functions to calculate P-ATR20, i.e. resulting from a pulse emission, the network-related studies apply AirClim as a climate chemistry model to calculate the F-ATR20 and F-ATR100, i.e. sustained emissions for a multiple year scenario. In both categories, CO_2 and non-CO_2 species were considered. Furthermore, trajectory-related OIs are investigated for a selected set of days to incorporate realistic weather effects in the determination of the climate metrics. Conversely, the network-related studies assume climatological mean values and thereby cover the full year of 2018. By contrast, the ground-related OIs calculate ATR according to the formula by Sausen and Schumann [27], focusing on CO_2 emissions in a typical year of operations.

Nevertheless, assumptions within the three OI categories have been aligned in the definition process, so that a semi-quantitative approach can be deployed to enable a comparison of the outcomes within the categories. On this basis, the comparison can further be extended to compare results from all inflight OIs. A description of the approach is subject to the present section.

The results from the different trajectory-related studies can be scaled to a comparable scope by taking the different restrictions and limitations of the individual studies into account. The initial situation is displayed in Table 13. A common denominator is defined per boundary condition (temporal scope, geographic scope and restriction of aircraft types) so that results can be adjusted to an equivalent basis and enable a comparison.

Table 13: Modelling assumptions and boundary conditions of the selected trajectory-related OIs.

	LOSL	FREE/WIND	CLIM
Climate metrics	ATR20 (pulse) with aCCFs CO_2, NO_x (CH_4 + O_3), H_2O, Contrails		
Non-climate KPIs	Trip Fuel, Trip Time, Flight profiles from Trajectory simulations[6]		
Temporal scope	4 selected days in 2018	1 selected day	4 selected days in 2018
Aircraft types	A330 + B777 A320 + B737	B737-800	A330 + B777
Geographic scope	From/to ECAC Intra-ECAC	En-route airspace (EDUU)	From/to ECAC (long-range)

For the trajectory-related OIs, the selection of a comparable day provides a temporal baseline which is similar in all three sub-studies. In this case, December 11, 2018 can be selected for an individual day case study. This day is investigated for an implementation of all OIs. Alternatively, results can be scaled up to the full annual scope based on the selected representative days.

The restriction to different aircraft types can be scaled to the full European scenario according to the covered Available Seat Kilometres (ASK) by the respective aircraft types in comparison to the full amount of ASK. For instance, LOSL covers 36% of all ECAC ASK of that day. Therefore, the total climate mitigation potential is scaled-up proportionally to all other aircraft types of the full scope.

Selected geographical airspaces will be scaled according to the presented approach by Dahlmann et al. [28] which does not only include dependencies of the fuel consumption but also latitude and distance of the analysed missions. This is essential as emission locations significantly influence the climate impact determination of non-CO_2 species. For this purpose, the scaling approach as presented below will be applied following this deliverable:

a. To extend results from a selected en-route airspace to the full mission from origin to destination, a scaling factor a based on ASK is applied:

$$a = \frac{ASK_{OD}}{ASK_{airspace}} \tag{1}$$

where $ASK_{airspace}$ represents all ASK covered in the respective airspace and ASK_{OD} the ASK covered by all missions from origin to destination through that airspace.

b. A further scaling of the results is based on the climate response calculation according to the formulas in [28]. These enable us to incorporate location dependent effects in the scaling process by determining a simplified scaling factor b. In this context, the climate response from non-CO_2 emissions can be determined from the CO_2 climate impact, latitude mean between origin and destination as well as the mission distance:

[6] A comparability of different trajectory calculation models has been proved in a comparison of emissions along selected highly frequented routes.

$$ATR20_i = (1 + F_{non-CO2,i}) \cdot ATR20_{CO2,i} \quad (2)$$

$$F_{non-CO2,i} = f\left(L_{origin,i}, L_{destination,i}, D_i\right) \quad (3)$$

ATR20 for a single flight i ($ATR20_i$) is derived from ATR20 from CO_2 emissions ($ATR20_{CO2}$) and a scaling factor for non-CO_2 emissions ($F_{non-CO2,i}$) as a function of latitude of origin and destination ($L_{origin,i}, L_{destination,i}$) and the great circle distance between origin and destination(D).

These values can then be applied to calculate an airspace specific scaling factor of the results:

$$b = \frac{\sum_{i=1}^{M} \quad ATR20_i}{\sum_{i=1}^{N} \quad ATR20_j} \quad (4)$$

where M is the set of all flights of the considered day that are applicable to the study and N is the set of flights going through the selected airspace.

c. The subsample results can then be scaled to the full scope of all European fights of the selected day with

$$ATR20_{full} = a \cdot b \cdot ATR20_{airspace} \quad (5)$$

where $ATR20_{airspace}$ defines the obtained ATR20 from the respective study and $ATR20_{full}$ is the corresponding ATR20 for the full European scope.

A similar approach can be applied when comparing results from the network-related OI category. However, the temporal dimension can be excluded as both studies incorporate a full year of operations. While results from NETW will be scaled according to the ASK covered by the three representative airlines, ISOC results have already been presented for the full scope. In this course, it needs to be taken into account that ISO is only expected to be beneficial and thus implemented for long-range operations with a great circle distance of more than 2500 nautical miles (see Table 14).

Table 14: Modelling assumptions and boundary conditions of the selected trajectory-related OIs

	NETW	ISOC
Climate metrics	ATR20 and ATR100 (sustained) with AirClim	
Non-climate KPIs	Trip Fuel, Trip Time, Flight profiles from Trajectory simulations	
Temporal scope	Full year 2018	Full year 2018
Airline types	Three representative airline types	All operating airlines
Aircraft types	All types available in the representative airlines fleet	Long-range aircraft
Geographic scope	Flight from/to ECAC area of selected airlines	Flights from/to ECAC area with a distance > 2500 NM

3.4 Applicability of the OIs considering the effect on stakeholders

Despite their mitigation potential, the effectiveness of the OIs depends also on the acceptance of the stakeholders. For any operational changes to be accepted and implemented, it is necessary to account for the drawbacks caused to all the different stakeholders. These considerations will be the object of the WP3, together with an analysis of the potential policies to mitigate such drawbacks. In this section, we present a preliminary overview of the impact of the OIs on the stakeholders, based on the analysis of the non-climate KPIs and various activities carried out during the ClimOP project. More details on the analysis of the impact on stakeholders are reported in Appendices B, C and D.

Flying low and slow leads to higher costs for the airlines. Aircraft are designed to fly at an optimum cruise level of 30.000 feet MSL and above. Flying below such optimum flight level results in a higher fuel consumption and consequent CO_2 emissions. Based on our analysis, on average, the cost increase due to higher fuel consumption is rather limited. Besides the higher fuel costs, this leads to increased carbon trading charges (i.e., CORSIA, ETS). Parallel to this, flying slower implies longer travelling times, and hence higher costs for crews. In a long-term perspective, it can be possible that a subsequent change of aircraft types and fleet, such that they are optimised for the new cruise level, is necessary. Concerning the management of the airspace, this OI implies reducing the usable airspace, and hence concentrating more traffic in the same airspace volumes. This will lead to a reduced capacity of the airspace, with more likely occurrence of delays, and an increase in the ATC workload. An upgrade of the Communications, Navigation and Surveillance (CNS) infrastructure would support low accident rates and controller workloads Finally, the ClimOP survey showed that the majority of passengers are willing to accept longer flight times or ticket prices, if associated with an ecological benefit.

There are no major issues in the application of Free routing and wind-optimised flight planning. The free routing is currently being deployed by the whole EU-27 member states [29]. To further optimise the flight planning, an advanced wind/weather forecast system would be necessary. There is already an attempt to create such a system. The global Aircraft Meteorological DAta Relay (AMDAR) program has been initiated by WMO (World Meteorological Organization) and its members in cooperation with aviation partners. Furthermore, an improved communication system can also enhance the system performance when a dynamic flight planning strategy is implemented based on the updated forecasts. The communication between the dispatcher and pilot can be ensured via the existing Aircraft Communication and Reporting System (ACARS) datalink unit. However, the improved communication between the pilot and ATC with an advanced system such as the controller-pilot data communication (CPDLC) could help to improve the performance in a dynamic flight planning setting.

The climate-optimised flight planning requires comprehensive (spatially and temporally high-resolution) information on the climate impact of aviation emissions. Similarly to what discussed for the Free routing and wind-optimised flight planning, such a weather observation system should be enhanced as a result of a continental effort. Moreover, as for Flying low and slow, new constraints and restrictions in the airspace reduces capacity, and might accentuate the capacity crunch problem once the traffic levels are restored as in pre-COVID pandemic times. Finally, the need to account for climate information on the flight planning will affect the workload of ATC.

The Strategic planning OI investigates the trade-off between profit and climate impact by including ATR20 in the optimization plan. This procedure implies the integration of new parameters and procedures into the existing decision-making process of airline planners and schedulers. The team composition, task allocation and communication means are not expected to change because of this OI. However, the way the information about ATR20 is conveyed to the airline planners might result in the need for ad-hoc training courses to facilitate the transition phase from one decision-making process to another. Finally, the ClimOP survey clarifies that passengers prefer less frequent flight connections and larger, fully-booked aircraft rather than baggage limitations.

The climate-optimised intermediate stop-over is rather complex to implement. For airlines, this OI might result in increased costs related to wide bodies decommissioning, as well as increased costs for the acquisition of a larger number of aircraft to accommodate the same passenger demands, increased operational times that imply increased operating costs of flight and cabin crews, increased costs on maintenance turnarounds, as the airframes will be subject to excessive number of jumps and increased cost on insurance and airport fees, as an additional airport should be used in comparison. Airport Operators will need to design and build the infrastructure for new airport hubs for intermediate refuelling to be served with appropriate and more sophisticated airspace infrastructure than the one used in oceanic and remote continental en route. More specifically, a CTA or TMA should be put in the middle of the Atlantic. Inserting compulsory TMAs in between the route would cause an increase in terms of ATC workload. Adding one stopover per oceanic and long-haul continental routes, implies to perform two times the number of landings and take-offs. This might increase and possibly double the inherent levels of risks associated with the normal operations.

For the ground-related OI, the main limitations are not technical, as the three OIs are based on mature technology, but rather economic and operational. Large investments are necessary to deploy the three OIs, as they all require, at different levels, a change to the airport infrastructure. For example, to enable electric towing it is necessary to purchase a sufficiently large fleet of electric tugs to guarantee efficient taxiing operations and also to redesign the airport ground to create specific areas for the coupling and decoupling of the tugs. Charging stations would be required for the tow trucks and all other electric vehicles and equipment. Also, the number of movements in the terminal manoeuvring area will increase because the tugs will need to reach their position to tow the departing and landing aircraft. All electric vehicles will need to move to and from the charging stations to refill more frequently than fossil-fuel-based vehicles currently do. These additional movements will consequently increase the workload for drivers and air traffic controllers. In addition, the airport operations would change in ways that could potentially alter the costs and revenues of different stakeholders. For example, electric towing would imply reduced fuel costs for the airlines but additional costs for the stakeholder responsible for the taxiing operations.

3.5 Qualitative comparison of the OI assessments

To summarize the work carried out in WP2, the ClimOP consortium designed a qualitative matrix to analyse the results. For each OI, the climate and non-climate KPIs are classified into 5 categories, corresponding to 5 different colours: strong positive impact, positive impact, neutral impact, negative impact and strong negative impact. When the KPIs are not significant, we use a different colour to display that there is no impact. The climate KPIs are summarized into three categories: CO_2 climate impact, non-CO_2 climate impact and total climate impact. It is worth stressing the importance of the non-CO_2 effects on the total climate impact. Although counterintuitive, some OIs have a positive impact even though they lead to an increase in CO_2. This is because the non-CO_2 effects are dominant in the overall climate impact evaluation. As an overview of the non-climate KPIs, we considered the maturity of the OI. This is the only column that does not follow the same categorization. Furthermore, we display the operational and economic impact on different stakeholders: airlines, airports and ANSPs. The matrix shows the importance of supporting the stakeholders in the implementation of these OIs, if they will be implemented. WP3 is aimed to recommend the optimal policies to make these changes possible.

OI	CO_2 climate impact	Non-CO_2 climate impact	Total climate impact	Maturity	Operational impact			Economic impact		
					Airlines	Airports	ANSPs	Airlines	Airports	ANSPs
LOSL				Medium						
CLIM				Medium						
FREE WIND				High						
NETW				High						
ISOC				Low						
SETX				High						
ELEC				High						
INFR				High						

Strong positive impact

Positive impact

Neutral impact

Strong negative impact

Negative impact

No impact

Conclusion and recommendations

This deliverable presents the results of the second assessment of the analysed OIs. Nine OIs have been selected during the previous activities of WP1, covering three different categories: network-related OIs (two OIs), trajectory-related OIs (three OIs), and ground-related OIs (three OIs). The assessments include both climate and non-climate KPIs, to account for the impact on the stakeholders, including airlines, airports, ANSPs and passengers. As such, it is a bridge towards the more detailed work that is carried out throughout WP3. Furthermore, different OIs have been combined into unified scenarios to explore the opportunity for synergies among OIs of the same category. An overview of the basic hypotheses and assumptions used in each assessment is also presented to put the results into the right context. Moreover, each OI entails uncertainties due to these assumptions and other choices made during the calculation. A detailed discussion of the sources of uncertainties and a first estimate is also included in the assessments.

The collected information is used to have a qualitative comparison of the results. The OIs are analysed based on their impact on climate and on the stakeholders. The ClimOP consortium decided to provide the reader with a comprehensive overview of the climate assessments, but to compare the overall results only on a qualitative level. The reason for this choice is twofold. On the one hand, it is not trivial to compare the different KPIs on a quantitative level and in a consistent manner, because of their different nature. On the other hand, further work for harmonizing the climate assessments is necessary. Different OIs require different approaches and modelling tools to be studied. This is an unavoidable challenge that need to be addressed in the post-processing. The entire research community is struggling to find an optimal way to address this problem. The ClimOP consortium has already designed a strategy to embrace the challenge, and make a step forward in the comparison of the OI assessments.

In conclusion, the analysis clearly shows that all the OIs are promising to reduce the climate impact of aviation. However, all of them entail an impact of the stakeholders due to changes in the operations and hence viable business models. In particular, airlines are affected by the proposed OIs as well as ANSPs and airports. Another difference is the maturity level that make them potentially applicable on different timescales. It is, then, worth stressing the importance of future work in the WP3 of ClimOP. A detailed analysis of the existing policies and informed recommendations on how they could be adapted to support the necessary changes to make these OIs operational is indeed necessary. Without this support, the considered OIs would be hard to accept from the aviation community.

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Appendix A: Detailed description of the OI assessment

The present appendix presents a detailed description of the OI assessment summarized in Section 2. This description is to be intended as an in-depth overview of the work carried out, while Section 2 is a compact version of these assessments to foster comparability.

A.1 Flying low and slow

To increase fuel efficiency and among others reduce direct operating cost (DOC), aircraft typically fly at optimum altitudes and perform step-climbs to higher flight levels with increasing flight length. In doing so, not only fuel consumption but also climate impact from CO_2 emissions is reduced as CO_2 effects are independent of the emission location. However, non-CO_2 effects, such as from H_2O, contrails, and NO_x, contribute to a major share of aviation's climate impact [30]. In contrast to effects caused by CO_2, the climate impact of non-CO_2 emissions varies widely depending on the location, altitude, time and environmental conditions of the respective emissions. Various studies have analysed the approach to reduce these effects by flying lower and shifting emissions to less climate-sensitive altitudes [31]. This in turn is associated with higher fuel consumption and thus CO_2 emissions as aircraft deviate from their fuel-optimal altitude profile. Therefore, an additional reduction in flight speeds is considered to diminish the unwanted rise in fuel consumption and CO_2 emissions.

To incorporate effects from different atmospheric boundary conditions, different meteorological situations and long-term climatological changes are considered in this analysis. Therefore, this study is divided in three parts, each of which deals with different boundary conditions and assumptions. Reduction potentials in ATR20 are provided and compared to associated increases in fuel consumption and flight time, which limit implementation attractiveness from a Stakeholder's perspective. Further implications of safety and passenger acceptance are considered.

Methodology

The study is divided into three sections, all with a different research focus:

1. *Baseline study:* This study investigates the climate impact on the selected days (winter and summer) based on actually flown point profiles and real atmospheric data. This study aims to confirm the mitigation potential of flying low and slow in general for long- and short-range flights. A first indication of meteorological impact can be derived from differences between the two days.
2. *Meteorological study:* Based on days representing the different seasons in 2018, this study investigates the mitigation impact of flying low and slow as a function of different seasons. For this purpose, a set of comparable flights is defined without considering day-specific point profiles or altitudes to ensure maximum comparability across the different seasons.
3. *Climate change study:* To assess the impact of long-term climatological changes, representative days for the three periods from 1991-2020, 2021-2050, and 2051 -2080 are identified based on 30-year-mean temperature and humidity profiles for the Northern hemisphere, divided in summer (JJA) and winter (DJF) seasons, and for climate projections for the different shared socio-economic pathways (SSPs) SSP1-2.6 and SSP2-4.5 [32]. Due to missing information about the future climate, this study is limited to the evaluation of contrail distances.

A summary of the differences between the different sub-studies is summarised in Table 15.

Table 15: Different variations of cruise flight level and speed defining different scenarios of OI implementation.

	Sub study		
	Baseline	**Meteorological**	**Climate-change**
Selection of representative days	summer & winter day Based on DWD classification	4 days based on DWD classification (1 per season)	one day per period based on temperature and humidity profile
Geographical scope	flights from/to ECAC, Intra-ECAC flights	flights from/to ECAC	flights from/to ECAC
Selected aircrafts	Airbus A330, Boeing 777 Airbus A320, Boeing 737	Airbus A330, Boeing 777	Airbus A330, Boeing 777
Selected flights	no additional restriction	only flights that are performed on all four days	equal to Meteorological study
Lateral trajectory definition	detailed point profiles	great circles	great circles
Vertical trajectory definition	step climbs of reference case according to detailed point profiles	constant flight levels	constant flight levels
Climate KPIs	Emissions, ATR20	Emissions, ATR20	contrail distance
Calculation of Climate KPIs	aCCFs	aCCFs	simplified contrail formation criterion[7]
Non-climate KPIs	flight time, fuel burn, DOC, selected flight levels, safety, passenger acceptance	flight time, fuel burn	flight time, fuel burn

[7] A simplified contrail formation criterion is applied. It is assumed that contrails form at a temperature T < 235 K, and are persistent for relative humidity over ice (RHI) > 90%

The modelling workflow and the utilised database have already been described in Deliverables D2.1. D2.2, and D2.3 [9][10][11]. A summary of the workflow is shown in Figure 7.

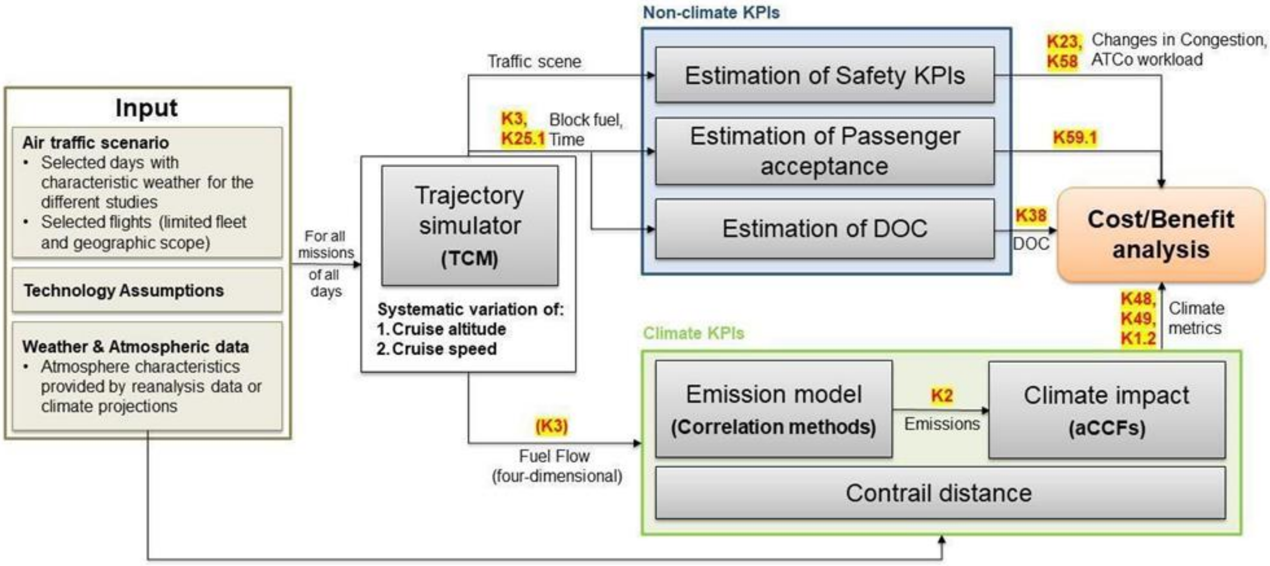


Figure 7. Modelling workflow for operational improvement of 'Flying Low & Slow'

A selected air traffic scenario on selected representative days, as well as the respective atmospheric data in terms of temperature, pressure, wind, and relative humidity, represents the input for the simulation workflow together with technological assumptions to be taken. The analysis is focussed on the most relevant aircraft types for long-range flights from/to the ECAC area and short- and medium-range flights within the ECAC area according to covered available seat kilometres (ASK). Consequently, A330 and B777 for long-haul flights and A320 and B737 are selected for the intra-ECAC subsample. Representative days are selected based on a classification by the German meteorological service (DWD) [14] for the analysis of 2018 and by the selection of most representative days in terms of temperature and humidity profile for the climate change study. Depending on the sub-study, detailed point profiles as provided by EUROCONTROL [33] or assumptions of great circles are considered.

The selected flights are fed into DLR's TCM to calculate the fuel flow along four-dimensional trajectories for every flight. In this context, an average European load factor of 84% is assumed [34] and flight performance characteristics according to BADA4 [35]. Central to the simulation of this OI is the systematic variation of cruise flight level and speed during the trajectory calculations. The reference case is typically characterised by the status-quo of how the flight was performed on the selected day. It is typically characterised by not constant flight level due to step climbs and descents that are performed for fuel efficiency or air traffic (ATM) related reasons. A first adjustment is flying on a constant flight level, that is defined by the cruise altitude which was chosen for the longest time during the flight (main flight level). This scenario is the basis for a reduction of cruise flight levels. Based on this main flight level, reductions are performed in 2000ft steps. Moreover, cruise speeds as determined by BADA4 speed schedule can be reduced by 5% and 10%. The different scenarios are summarised in Table 16. Due to different wind conditions and depending on the given speed in the schedule (CAS or Mach), implicit changes in the cruise speed are possible even if no explicit speed change is defined.

Table 16. Different variations of cruise flight level and speed defining different scenarios of OI implementation

		Cruise speed adjustment		
		No explicit speed change	**- 5%**	**- 10%**
Cruise flight level adjustment	**No change (not constant)**	Reference case 1	-	-
	Constant	Reference case 2	-	-
	- 2000 ft	Scenario 1.1	Scenario 1.2	Scenario 1.3
	- 4000 ft	Scenario 2.1	Scenario 2.2	Scenario 2.3
	- 6000 ft	Scenario 3.1	Scenario 3.2	Scenario 3.3

The trajectory output of position, altitude, time increment, atmospheric background conditions and fuel flow is used to calculate the emission flows for each time step individually. CO_2 and water vapour emissions are linear to fuel burn, nitroxides (NO_x) are modelled with the fuel flow correlation method by DLR [12]. With the algorithmic climate change functions (aCCFs) for CO_2, ozone, methane, water vapour and contrail induced cirrus clouds it is possible to calculate the instantaneous climate impact for each species individually. Daily and seasonal variation and the effects of latitude on solar irradiance are regarded by the aCCF as well as atmospheric conditions of temperature, humidity and potential vorticity. The timestep-specific climate impact will be aggregated along the entire trajectory to obtain the total climate impact per individual flights. For further details please refer to the description of aCCFs in [13], which have been utilised in an adjusted form for this study.

To ensure implementation attractiveness from a Stakeholder's perspective, the analysis of the climate impact in terms of ATR20 reduction is broken down into different options of allowable fuel and time penalties. In doing so, climate-optimal solutions can be restricted regarding the extra fuel and time needed for the individual mission. This is the basis to derive pareto-fronts to comprehensively assess the implementation of this OI not only from a climate but also from a stakeholder's perspective. Impact on non-climate KPIs such as direct operating cost, safety, and passenger acceptance are estimated based on the simulation results in flight time, fuel consumption, and selected flight levels.

Results

A. Assessment of climate KPIs

Baseline study

Table 17 shows the results for a single mission from Newark (United States) to Porto (Portugal) with an Airbus A330-243 on June 16, 2018. The reference flight departs at 01:41 UTC and takes approximately 6 hours and 13 minutes. Significant reductions in ATR20 can be achieved by reducing flight level and speed. The climate optimal scenario is defined by a flight level reduction of 4000ft to 37,000ft and a speed reduction by 10% to Mach 0.74. This is mainly due to contrail effects, as contrail distance is reduced with a flight level decrease. Figure 8 (a) illustrates this correlation. As climate impact from CO_2 and H_2O does not significantly change, contrail distance is mainly reduced by shifting down to lower cruise flight levels. At FL350 there is almost no climate impact from contrails to be observed. While NO_x emissions scatter between +15% and - 8% for the different scenarios, it can be observed that emission quantities increase with lower flight levels and decrease with lower cruise speeds. Furthermore, ATR20 from nitroxides rises with lower flight levels and faster flight speeds (see Figure 8 (a)). For flight level reductions between 2000ft and 4000ft, this effect is overcompensated by contrail effects on ATR20, but not for flying 6000ft lower. Figure 8 (b) provides an overview over contrail forming regions and confirms the longer distances through contrail forming regions at higher flight levels. Since the flight is mainly performed during night time, contrails mainly induce warming.

However, the optimal solution according to scenario 2.3 is associated with a significant increase in flight time (+ 7.35%) and a slight increase in fuel consumption (+ 0.64%). From an operator's perspective, it might make sense to limit extra fuel and time. If both limits are set to 5% for instance, scenario 2.2 (- 4000ft FL, - 5% speed) is the optimal one and still provides significant mitigation potential (- 58.58%). Even stricter limits (e.g. maximum 2% extra fuel and time) are associated with high mitigation potentials in this case (- 52.97%).

Table 17. Mitigation potential for flight from Newark (US, KEWR) to Porto (Portugal, LPPR) with an Airbus A330-243 on June 16, 2018 for different implementations of flying low and slow.

	CFL [100ft]	Cruise Mach [-]	Fuel [t]	Emissions CO_2 [kg]	Emissions NO_x [kg]	Contrail distance [km]	Flight Time [-]	ATR20 [10^{-11} K]
Reference case 1	410	0.82	32.53	10,248	421.86	976.16	6.22	29.80
Reference case 2	410	0.82	- 0.06%	- 0.06%	- 0.36%	- 1.67%	- 0.30%	- 4.16%
Scenario 1.1	**390**	**0.82**	**+ 1.29%**	**+ 1.29%**	**+ 1.00%**	**- 47.25%**	**- 0.93%**	**- 52.97%**
Scenario 1.2	390	0.78	- 1.27%	- 1.27%	- 7.13%	- 47.07%	+ 3.30%	- 53.49%

Scenario 1.3	390	0.74	- 0.77%	- 0.77%	- 9.82%	- 46.16%	+ 7.89%	- 53.08%
Scenario 2.1	370	0.82	+ 4.79%	+ 4.79%	+ 6.88%	- 81.67%	- 1.59%	- 57.29%
Scenario 2.2	**370**	**0.78**	**+ 1.50 %**	**+ 1.50 %**	**- 2.96%**	**- 81.71%**	**+ 2.65%**	**- 58.58%**
Scenario 2.3	**370**	**0.74**	**+ 0.64%**	**+ 0.64%**	**- 8.12%**	**- 81.44%**	**+ 7.35%**	**- 59.13%**
Scenario 3.1	350	0.82	+ 9.61%	+ 9.61%	+ 15.67%	- 89.74%	- 2.33%	- 51.70%
Scenario 3.2	350	0.78	+ 5.26%	+ 5.26%	+ 3.20%	- 89.98%	+ 1.91%	- 53.49 %
Scenario 3.3	350	0.74	+ 3.24%	+ 3.24%	- 4.31%	- 89.86%	+ 6.61%	- 55.67%

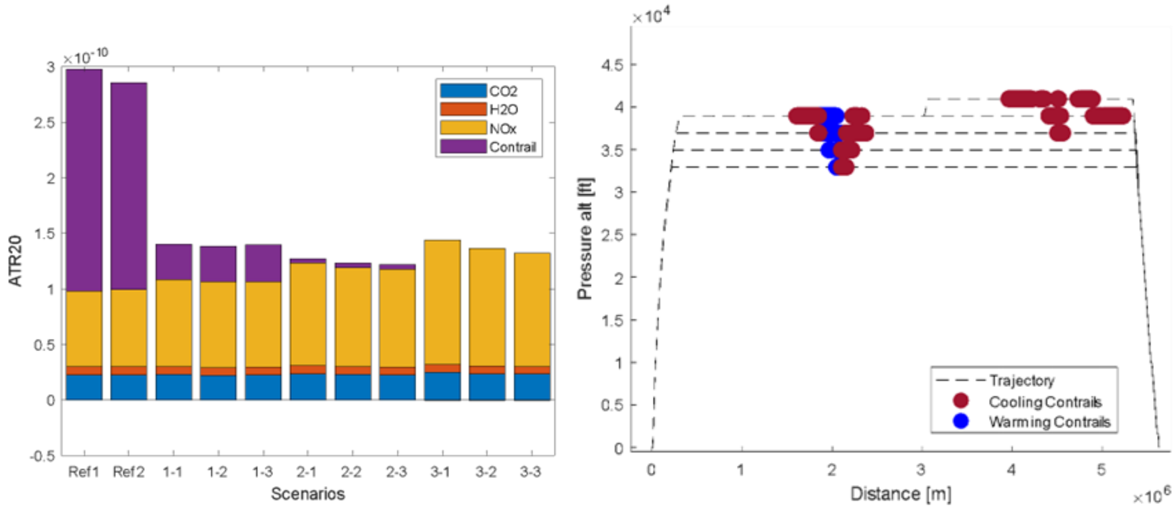


Figure 8. ATR20 for different emission species (a, left) and contrail formation regions (b, right) along trajectories.

These results can be summarised for the selected flight plans and for different combinations of fuel- and time penalties. For the selected summer day of June 16th 2018, an ATR20 of 0.486 µK can be observed for the selected European scenario that covers 36% of all ECAC ASK of that day. The total climate mitigation potential is 11.4% for the selected day, which is equal to an absolute reduction of 0.055 µK. Allowing additional fuel consumption and extra time of 5% per flight, enables reduction of ATR20 by 9.9% by flying lower and slower, while keeping extra fuel flow and time within certain limits. An allowed penalty of 1% is associated with a climate mitigation potential of 2.6%.

Figure 9 (left) illustrates the distribution of climate optimal cases over the selected scenarios for an allowed fuel and time penalty of 5%. A strong preference towards small reductions in flight level (mainly constant or - 2000ft) and a reduction in flight speeds by 5% in case of flight level reductions can be observed. This compilation is influenced by the allowed penalties since lower speeds are typically associated with longer flight times and lower flight levels and remaining constant speed at the same time leads to increased fuel consumption. Distribution of climate impact over the different emission species in Figure 9 (right) shows that an implementation of the OI as described only negligibly influences overall CO_2, H_2O and NO_x impact (Climate impact change of +0.4% for CO_2, -5.6% for H_2O and + 0.6% for NO_x), but a majority of the reduction can be explained by a reduced contrail impact -75.7%. Furthermore, average extra fuel consumption is 0.36% and extra flight time is 1.26% for the 5% penalty case.

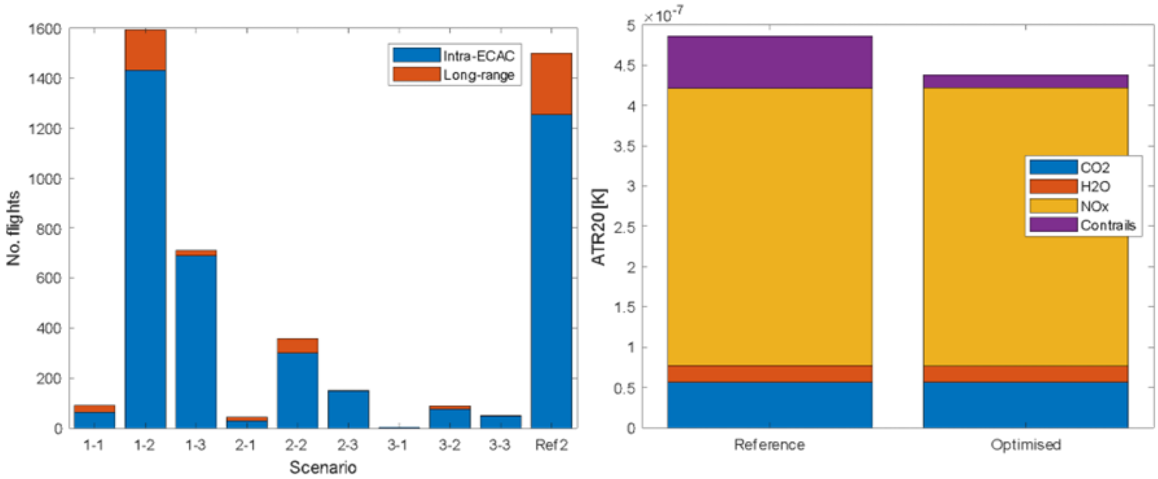


Figure 9. Distribution of selected climate-optimal scenario (a, left), Comparison of climate impact per emission species (b, right) for full European scenario on June 16,2018 with allowed fuel and time penalty of 5%

Besides flight altitudes and speeds, background atmosphere conditions and geographic location of the emissions influence the climate impact of the emitted species. For this purpose, detailed flight missions along actual point profiles for a winter situation (real atmosphere data from December 11, 2018) are calculated to assess comparability of effects for different seasons. Figure 9 compares the pareto fronts for the different days: a higher mitigation potential can be observed for the selected winter day in comparison to the summer day. Mitigation potential on December 11, 2018 can be quantified to more than 20%. These results remain robust for a sub-sample of the North-Atlantic region, where aCCFs have been validated.

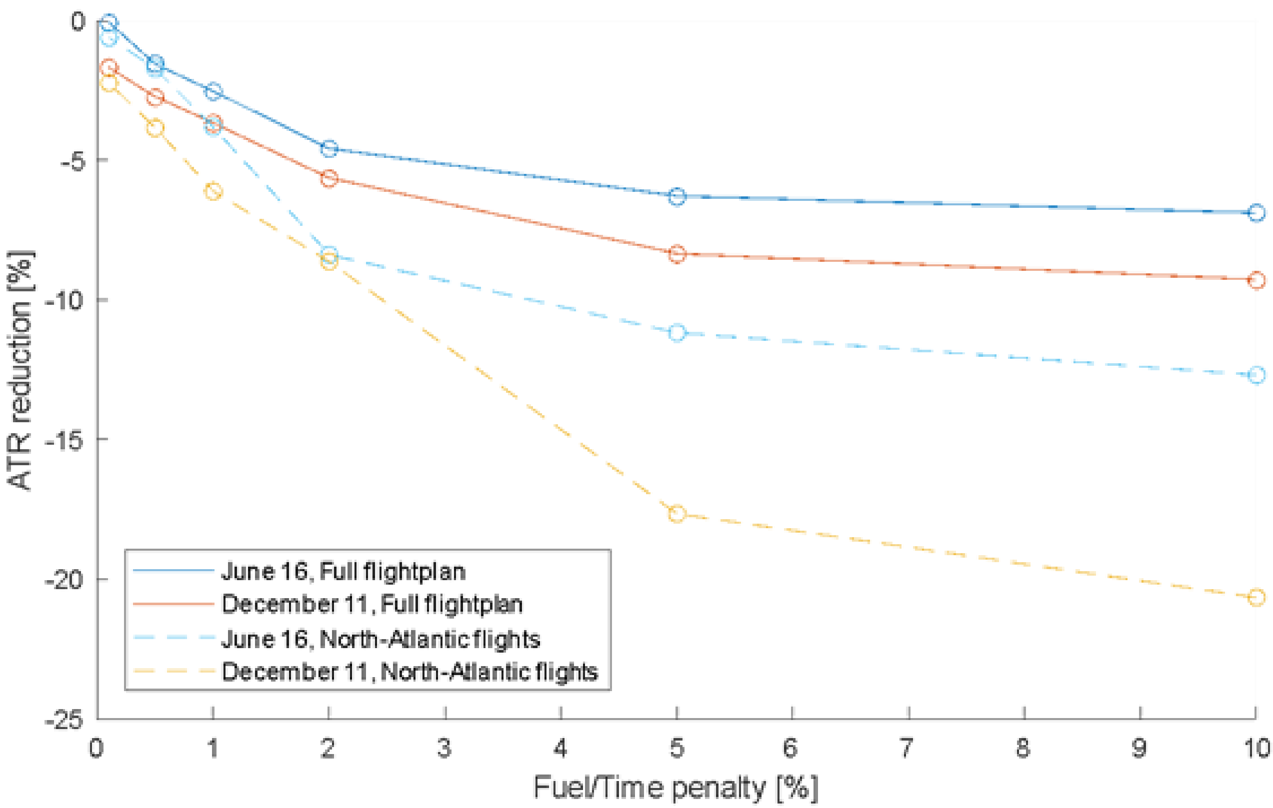


Figure 10. Assessment of climate mitigation potentials for selected days and flight plan sub-samples

Meteorological Study

Based on the outcomes above, the analysis aims to assess the climate mitigation potential of flying low and slow as a function of the different seasons and their respective representative weather situation. For this purpose, a set of representative flights is defined for the four representative days. This sample of flights consists of all long-range flights from and to the ECAC area with Boeing 777 and Airbus A330. It is further reduced to a consistent sample of flights, which are performed on each of the four selected days. Start time and flight level are selected based on the median of all performed missions on this origin-destination pair. The resulting flight plan consists of 157 different combinations of origin, destination and aircraft type.

Typically, during winter and early spring season the polar front jet stream is located southerly in north hemisphere mid-latitudes compared to summer and autumn with the consequence that cold air masses cover large parts of Europe and North Atlantic area. The amplitudes of planetary waves are also higher during selected winter and spring days that enables an enhanced humidity transport from moist air masses towards higher latitudes triggered by evaporation areas over relatively warmer North Atlantic sea surface. A strong jet stream and intense low-pressure systems around Iceland that are moving eastward are dominating seasonal weather patterns with observable higher wind speeds from western direction, large-scale cloud cover and frequent precipitation events. Those conditions favour the formation of contrails. In summer season and early autumn, the typical zonal pressure gradient between Azores and Iceland is distinctly lower that leads to a reduced dynamic in the atmosphere and enables the development of stable high-pressure systems with warmer air masses and rather dry weather characteristics. Such conditions could lead to a reduced contrail forming potential but an enhanced impact of NO_x on ozone driven climate impact during the summer season.

To ensure comparability between the different seasons, detailed point profile data are not applied in this case but use approximations of great circle connections and constant flight levels, that are derived from the median main flight levels of the different days. Resulting reductions in ATR20 for the different fuel and time penalties, confirm what has been observed in the baseline study (see Table 16). For the colder days in March and December, mitigation potentials are higher. Associated reduction potentials range from 2-4% in summer/autumn to 6-13% in winter/spring. Remarkable differences can be explained by striking variations in climate impact of the different species. NO_x effects are approximately 60-80% higher in June and September compared to March and December. Nevertheless, NO_x impacts are inferior to those caused by contrails, so that higher relative mitigation potential can be realised by flying lower and slower in winter and spring.

Table 18. Climate mitigation potential depending on extra fuel and time allowed for representative days in 2018

		Climate mitigation potential			
		Mar 28	**Jun 16**	**Sep 27**	**Dec 11**
Fuel/Time penalty	**1%**	-0.61%	- 0.01%	- 0.05%	- 0.07%
	5%	- 5.93%	- 1.34%	- 1.82%	- 4.72%
	10%	- 7.65%	- 2.07%	- 2.29%	- 7.15%

Numbers in the meteorological study are generally lower than in the baseline study. This can be explained by two reasons: (a) the sample of flights is smaller compared to the basic study and average flight times and levels are selected and (b) as the reference case is represented by a constant flight level, climate-unfriendly step climbs are already avoided, so that the reference climate impact is already reduced compared to the fuel-optimal case.

Climate change Study

The goal of the climate change study is to assess the effect of climate change on this OI over the long term. In particular, the goal is to understand the efficacy of this OI in reducing non-CO_2 effects, especially concerning contrail formation, with climate change transforming the atmospheric stratification. The key challenge is to capture how the atmosphere changes over the long term, hence how the climatological mean conditions vary with time, while including the local fluctuations in temperature and humidity that are essential for condensation and cloud formation. To this end, the concept of representative days is applied, defined as the days that best represent the atmospheric structure of the climatological mean vertical temperature and humidity profile. More specifically, the method for selecting the representative days entails the following steps:

1. Calculate the climatological mean profiles as the average profile of relative humidity and temperature over the Northern Hemisphere and the climatological time-windows of interest, 1991-2020 for present-day climate, and 2021-2050 and 2051-2080 for mid-term and long-term future climate;

2. Estimate the daily mean profiles over the Northern Hemisphere for each time-window of interest;
3. Sum the squared difference between the climatological mean and the daily mean profiles at each available pressure level, for relative humidity and temperature separately;
4. Rescale the previously obtained results (step 3) with a min-max normalisation such that they are comparable as they both range between 0 and 1;
5. Calculate the total metric to evaluate the representativeness of a specific day as the sum of the rescaled values for relative humidity and temperature (step 4);
6. Identify the day for which the metric is minimised.

Two separate analyses for summer and winter days are made. For present-day climate, ERA5, the latest reanalysis product of the European Centre for Medium-Range Forecast (ECMWF), is used for the climatological period 1991-2020. For future climate conditions, the climate projections available through the Coupled-Model Intercomparison Project 6 (CMIP6) are considered for the climatological periods 2021-2050 and 2051-2080. In particular, the focus is on the outputs of the model HadGEM3-GC31-LL for SSP1-2.6 and SSP2-4.5. Table 19 lists the representative days that are considered in the following analysis for the winter and the summer months and Figure 11 illustrates the temperature and humidity profiles for the selected winter days: For a majority of the pressure levels, both humidity and temperature are higher for the future predictions in comparison to the historical reference.

Table 19. Representative days used in the climate change study for winter and summer months

Data set	ERA5	CMIP6 SSP1-2.6		CMIP6 SSP2-4.5	
Climatological period	1991-2020	2021-2050	2051-2080	2020-2049	2050-2079
Representative winter day	23/13/2000	09/01/2032	07/01/2073	26/01/2042	17/01/2057
Representative summer day	01/08/2015	05/07/2046	03/07/2074	04/07/2039	19/08/2050

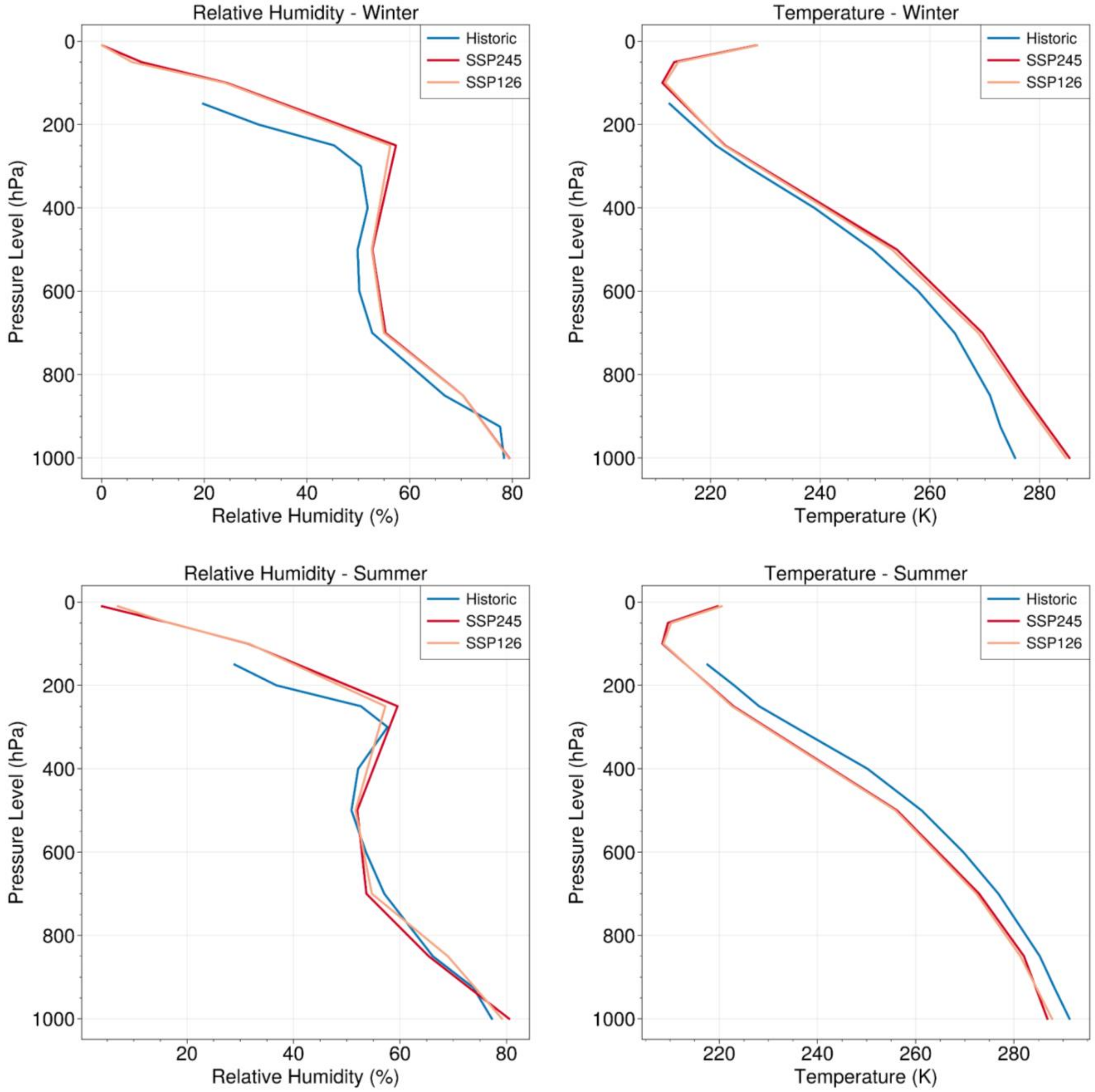


Figure 11. Temperature (left) and humidity profiles (right) for the selected winter days (top row) and summers days (bottom row) for historical and future projections (SSP1-2.6 and SSP2-4.5). Historic data are representative of the period 1991-2020, and future profiles of the period 2051-2080.

Figure 12 illustrates the contrail distance for the different considered periods and scenarios. As required climate data are only available on daily mean resolution, diurnal effects on contrail formation processes cannot be considered. The analysis of contrail distance is based on daily values of atmospheric data, so that trend in contrail distance development can be analysed. It can be observed, that the approach of flying lower to avoid contrails remains valid for future climatological developments in summer: For the years from 2051 to 2080, a stronger contrail mitigation effect by flying lower can be observed in comparison to the current climate, while there is no clear trend to be observed for the period from 2021 – 2050. Furthermore, it can be observed that contrail distances are lower overall, when comparing the different reference cases across the different time periods. By contrast, the winter situation shows a different relation. On average, humidity along the calculated trajectories increases while temperature rises (see Figure 11). Therefore, longer contrail distances can be observed for future scenarios compared to the status quo situation for the reference case as well as for a part of the cases with reduced flight levels. Thus, correlations and the approach of flying lower to reduce climate impact from contrails cannot directly be transferred to future scenarios. Further investigations will be required in this context.

In addition, it has to be noted, that results from this sub-study cannot directly be compared to the baseline as well as the meteorological study, as available atmospheric data for projections in contrast to reanalysis data and climate KPIs (Contrail distance instead of ATR20) significantly differ.

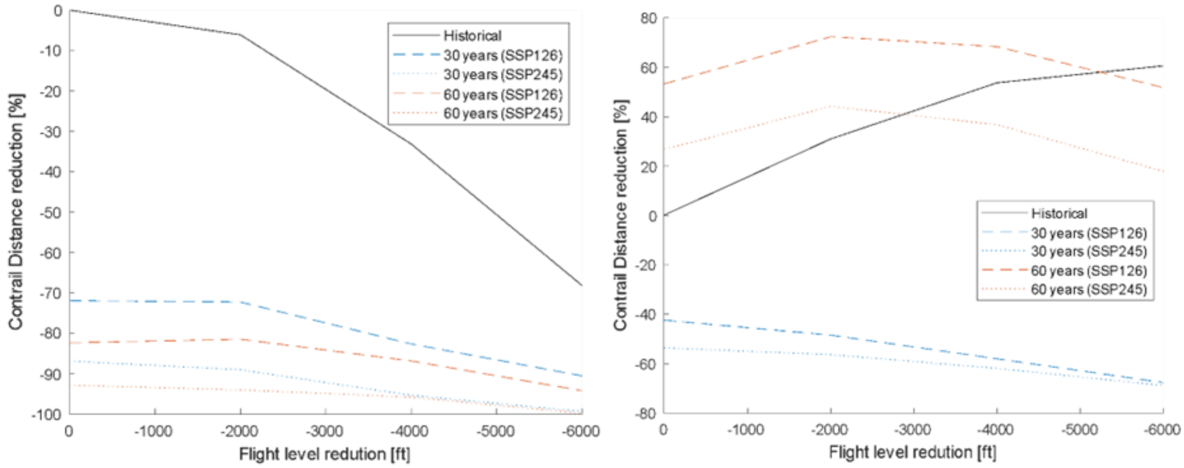


Figure 12. Relative changes in contrail distance due to flying lower based on representative days for historical period (1991-2020), 30-year future period (2021-2050) and 60-year future period (2051-2080) for summer (left) and winter (right).

B. Assessment of non-climate KPIs

Assessment of non-climate KPIs is focused on the main Stakeholders that are expected to face major consequences from implementation of flying low and slow. Therefore, the focus of the analysis is set on the following Stakeholders and associated KPAs and KPIs:

- Airlines: Fuel consumption, Flight time, Direct operating cost (Economic assessment)
- Air traffic control: Air traffic controllers' workload, accident rate (ATM and safety assessment)
- Passengers & Society: Passenger acceptance (Acceptance assessment)

Based on the results achieved in the simulation of climate impact, a detailed qualitative description of the effects of an implementation of LOSL on the different Stakeholders is followed by a quantitative estimation of the described KPIs.

<u>Economic assessment</u>

Flying lower and slower increases fuel consumption for most of the optimisation scenarios, which also leads to additional CO_2 emissions. From an airline's perspective, this increases operating cost from fuel overconsumption and carbon trading charges (EU ETS, CORSIA). Furthermore, flying lower impacts airlines' business models, among others due to additional operating expenses for flight and cabin crew.

Restricting fuel and time penalties to certain limits as discussed above, enables considerations on different levels of cost increase for the stakeholders, especially for the airline operating the flights. Based on an FAA estimation on direct operating cost composition [36], the following increase in Direct Operating Cost (DOC) can be estimated based on additional Fuel Cost, that are directly proportional to the additional Fuel Consumption, and other variable costs (such as crew expenses) that depend on the flight time and are scaled up based on the extra flight time.

Limiting additional fuel and flight time on the level of individual flights shows that on average, additional fuel and flight time and thus also DOC are significantly below those penalty limits. Details are displayed in Table 20. A more detailed analysis of direct operating cost changes due to flying lower and slower should be subject to further investigation following this study.

Table 20. Estimation of increase direct operating cost, depending on pre-defined fuel and time penalty for European flights on June 16, 2018

		Extra fuel average	Extra time average	DOC impact	Climate impact
Fuel-Time-Penalty	1%	+ 0.02%	+ 0.00%	negligible	- 2.61%
	5%	+ 0.36%	+ 1.26%	~ 1.0%	- 9.89%
	10%	+ 0.54%	+2.63%	~ 2.0%	- 11.37%
	Not limited	+ 0.57%	+2.82%	~ 2.5%	- 11.43%

ATM and safety assessment

Flying lower and slower affects the airspace utilisation and has consequences on the airspace users: Injecting the same load of traffic in a reduced airspace implies an overconcentration of traffic in the same airspace volumes, which will affect:

- Capacity impacts and ATFM delays: It is important to note that before the pandemic, the airlines flying in the EU were already experimenting a capacity crunch in the European ATM Network. Reducing the available airspace will accentuate the problem once the traffic levels are restored [37].
- ATC workload: changing the available airspace and the current FL allocations would cause an increase in ATC workload on the ANSP, which would generate a cascading effect of needs for additional ATC staffing. This would lead to an increase in air navigation services (ANS) costs, and therefore an increase in ANS charges for the airspace users (and more expensive tickets for the customers).

From a quantitative perspective, impacts can be estimated from the distribution of the different flight levels (Figure 13). For the selected intra-ECAC flights, it can be observed that cruise altitudes are shifted to lower levels when optimising flight levels and cruise altitudes with regards to climate impact. Nevertheless, observed flight levels do not overload the different flight levels: There are no disproportionate increases compared to the respective flight level and not more than 7% compared to the maximum utilisation observed over all flight levels, so that high safety can be maintained.

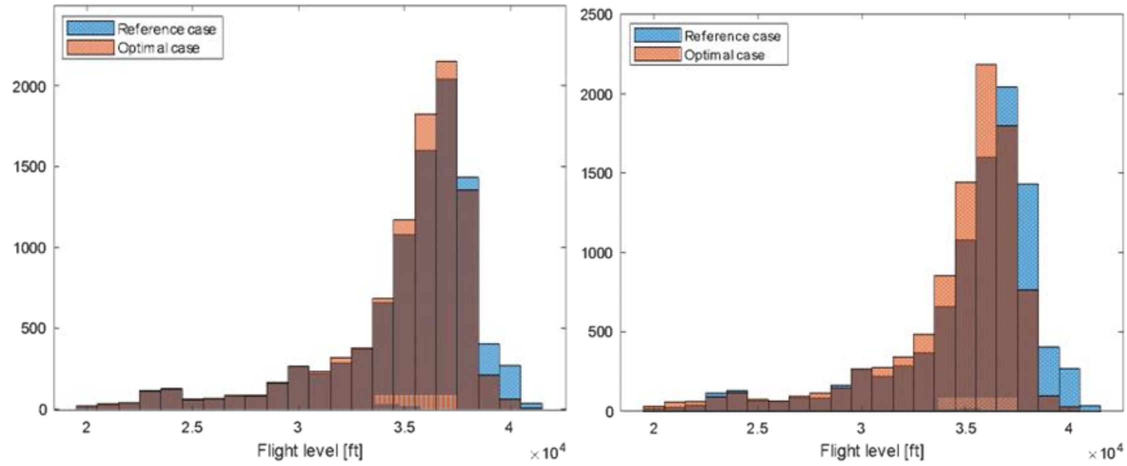


Figure 13. Comparison of frequencies of selected flight levels for Intra-ECAC flights (left: with fuel and time penalty of maximum 1%, right: maximum 5%)

<u>Acceptance assessment</u>

When assessing challenges of implementing operational improvements, not only consequences for airlines and air navigation service providers need to be considered, but also impacts on the passengers. Their decision to buy a ticket strongly influences the whole system of aviation.

In the context of flying low and slow, longer flight times lead to longer travels for the passengers and longer on-board times. fuel consumption and an increase in DOC could lead to higher ticket prices. On one hand, both aspects reduce attractiveness for the passengers potentially leading to a fall of flight ticket sales and thus airlines revenues. Especially on shorter continental routes, passengers might prefer existing transportation alternatives (e.g. train travels) over flying. On the other hand, it can be observed that ecological awareness of passengers influences their decision and a willingness to accept higher efforts if they are associated with a climate benefit.

To investigate this, a survey on passenger acceptance has been performed:

- The interviewees were asked first, if they would be in favour to pay an addition of up to 25% or 50% for a flight when flying lower to reduce its climate impact, on both short and long range.
  30% of interviewed persons are in favour to pay up to 50% more for a flight on short-haul range, further 31,8% would pay an enhanced fare of up to 25% when applying flying low. For travelling on long distance flights 40,1% of interviewees would pay an extra ticket fee of 25%, only 20,2% would spend even more money for the ticket (up to 50%). Unlike 23% of passengers do not want to pay a higher ticket fee on short-haul flights when flying lower and approximately 32% accept flying lower only when the fares will be kept constant.
- A second question for the interviewees should give information about the acceptance of flying slower and the linked travel duration. Results show that 41% of interviewees are totally in favour to accept a by 20% extended flight time on short-haul flights and further 23% are in favour to accept the longer flight in consequence of flying slower. For long distance flights an extension of flight time by 16% was asked in terms of acceptance. Again 23% of interviewees

are in favour of the extended flight time when reducing climate impact due to flying slower, 36% are totally in favour with that operational improvement on long-haul flights.

Therefore, a majority of interviewed passengers are going to accept both higher ticket prices or prolonged travel times when reducing ecological footprint.

C. Uncertainty estimate

For a reliable assessment of implementation impacts of this OI, an investigation of uncertainties incorporated in the modelling and simulation approach need to be considered. Two major uncertainties were defined and provide an estimation of their impact below:

Trajectory and emissions modelling uncertainties

In the process of remodelling the trajectory according to the defined flight profiles (laterally and vertically), some assumptions were made that have an influence on the results achieved. We focussed our analysis on the major impacts from our side, that are:

- **Assumption of an average European load factor:** To facilitate calculations without detailed TOW data information, an average payload per aircraft and a fuel planning approach aiming for maximum fuel efficiency was assumed. However, different approaches and different load factors are realistic on different flights, so that varying take-off masses are more realistic. This uncertainty was quantified by varying load factors of a global air traffic sample and comparing the resulting emission totals of the generated emission inventory. The seat load factor of each flight within the global flight plan that follows continental average values in the reference simulation is enhanced by 5 and 10 percent points and reduced by the same values in the course of the sensitivity study. The results show that an enhancement of all seat load factors by 5 percent leads to higher CO_2 emissions by 1.2% and NO_x emissions by 1.7% on a global scale compared to the reference scenario. Increasing all load factors by even 10 percent points results in 2.4% higher CO_2 and 3.5% higher NO_x emissions. Shrinking the load factors by 5 (10) percent points will reduce the total CO_2 emissions by -1.2% (-2.3%) and NO_x by -1.7% (-3.2%).
- **Assumption of BADA4 performance data and ICAO Emission indices**: To model aerodynamic and engine performance data along the flight trajectories, BADA4 performance data was utilised in this study.
- **Uncertainties from atmospheric boundary conditions**: Different atmospheric conditions significantly influence trajectories, their emissions but also the resulting climate impact. This uncertainty has been covered by incorporating different representative days with the respective meteorological situation. Among others, different wind situations influence Trip fuel and corresponding emissions as well as flight times. Deviation across the different investigated days is ±0.7% for fuel and ±2% for trip time according to the different atmospheric conditions of the selected days.

Climate impact modelling uncertainties

The second main source of uncertainty is modelling the climate impact of this operational improvement. Uncertainties result from model development of aCCFs on the one side and their adjustment in terms of scaling factors on the other side.

The applied aCCFs were adjusted compared to the published version [13] by different scaling factors. In the context of this OI's uncertainty analysis, a special attention has to be paid toward the climate impact of contrails. A reduction of the climate impact due to lower flight levels can mainly be explained due to the avoidance of contrail effects. These effects are typically subject to large uncertainties (see e.g. [33]). To consider these uncertainties, different scaling factors to the contrail aCCF were applied to investigate the robustness of the climate mitigation effects of flying low and slow. Figure 14 illustrates the achieved results in the form of different pareto fronts for contrail scaling factors of 0.1, 1 and 10. Therefore, it can be observed that climate mitigation results are robust for different scaling factors. However, they are significantly lower for smaller contrail scaling factors as mitigation impacts are highly dependent on contrail effects. Furthermore, the finding that mitigation potentials are higher in winter compared to summer remains true for a variation of contrail scaling factors in the given limits.

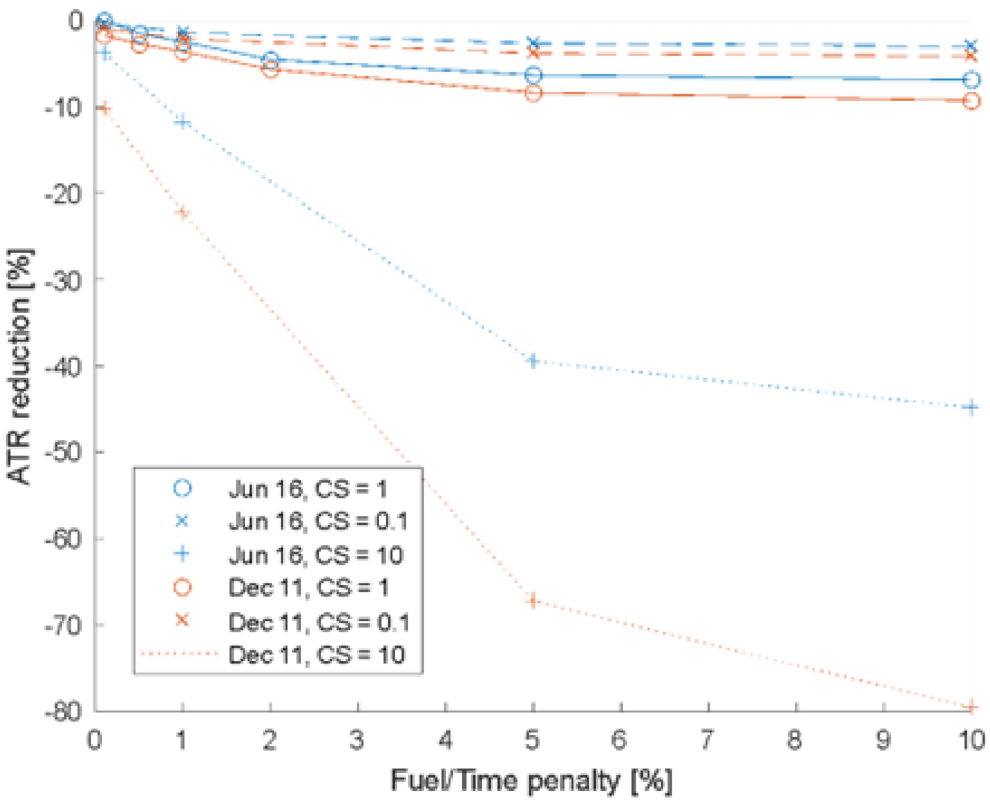


Figure 14. Pareto fronts for different contrail scaling factors on different days

D. Comparability of the results with the other OIs

Based on the analysis, results can be scaled to an aggregated European scenario. However, an extrapolation needs to be performed with care since results have only been calculated in detail for the selected scope and assumptions. Several restrictions, that have been taken in course of the modelling process need to be considered in this context:

- Geographical scope: For one selected day, no geographic restrictions have been performed, so that these results are representative for all flights from and to as well as within the ECAC area.

- Selection of aircraft types: The analysis was limited to four specific airline types, that covered a major share of all ECAC ASK. Assuming an equivalent correlation for the other aircraft types, a proportional relation between ATR20 and ASK was presumed, if the sample size is big enough and covers a large variety of routes and aircraft types. Thus, a maximum climate impact mitigation potential of 11% was hypothesised also for the full European scope.
- Temporal Scope: Results have been calculated for selected days. However, the methodology of selecting these representative days allows an up-scaling process to the full year of 2018. If we assume a maximum climate mitigation potential of 11% in summer/autumn and 20% in winter/spring, as well as an equal distribution of the representative days and consistency of ATR20 of the reference cases for the different weather situations, it is possible to estimate the full mitigation potential on this basis.

However, absolute numbers have to be handled with care especially when comparing results along the different operational improvements due to the wide range of assumptions made in the modelling process. Nevertheless, results can be directly compared across other trajectory-related OIs (FREE/WIND and CLIM), as climate-metric and modelling approaches as well as geographical and temporal scope are comparable. Furthermore, order of magnitude of absolute results as well as relative mitigation potentials can be used to compare LOSL with the other selected OIs.

E. Applicability of the OI

The operational improvement of flying low and slow is highly applicable to mitigate the climate impact of aviation. Benefits of implementing this OI are:

- No technical expensive technical adjustments to the infrastructure are required. However, an upgrade in CNS infrastructure would support implementation as safety issues and control workload due to higher utilisation of less climate-sensitive areas could be diminished.
- Although flying low and slow extends flight times and increases the required fuel per mission, on average cost increase due to implementation is limited.
- The OI of LOSL is suitable to be combined with other OIs to ensure additional mitigation gains (i.e with FREE, WIND, and/or ISOC).
- According to the passenger survey, a majority of the passengers are willing to accept longer flight times or ticket prices, if associated with an ecological benefit.

Conclusions

All in all, this study on flying low and slow confirmed a significant climate mitigation potential from this operational improvement. It confirmed the fact that flying lower to avoid climate-sensitive areas and thus reduce non-CO_2 climate impact can be combined with flying slower to compensate additional fuel consumption due to shifting to lower flight altitudes to reduce the climate impact of those flights. Overall mitigation potentials are highly dependent on allowed extra fuel and time, so that ATR20 reduction potentials vary between 2.6% (maximum 1% fuel and time penalty per flight) and 11.5% (no restrictions) for the selected representative summer day. This can mainly be explained by a reduction of contrail effects. Changes in fuel consumption and resulting CO_2 effects can be limited in the context of combining flying lower with flying slower. Furthermore, the observed mitigation potentials differ in dependence of the atmospheric boundary conditions in terms of meteorological and long-term climatological situation. It was observed that climate-mitigation potentials are higher in winter and spring and cannot be directly transferred to future climate situations. Different geographical scopes also impact ATR reduction potentials.

Due to the compensation of extra fuel consumption, additional direct operating cost from implementing this OI remains limited. Nevertheless, increasing flight times can lead to a limited attractiveness of implementing this OI. From an air traffic management perspective, a higher utilisation of climate-friendly flight levels can lead to additional implementation challenges. Upgrades in CNS infrastructure will help tackle these challenges.

A.2 Free routing and wind-optimised flight planning in high-complexity airspace

The free routing concept provides an opportunity to plan the trajectories without being restricted by the standard air traffic service (ATS) routes. The concept can reduce the travel duration, fuel consumption, CO_2 and non-CO_2 emissions depending on the preferred trajectories. The OI covers the implementation of the free routing concept in high complexity airspace using shortest paths and advanced flight planning tools by prioritizing different objectives and considering wind information. By applying different planning strategies, the study investigates how the flexibility in the free routing concept can be exploited via different objectives and evaluates which impacts can be experienced by main stakeholders for these planning strategies.

Methodology

The study mainly focuses on the implementation of the free routing concept in high-density en-route airspace in ECAC area. The specified en-route airspace (EDUU) and model workflow have been presented in Deliverables D2.3 and D1.5 [11] [8]. A summary of the model workflow is given in Figure 15.

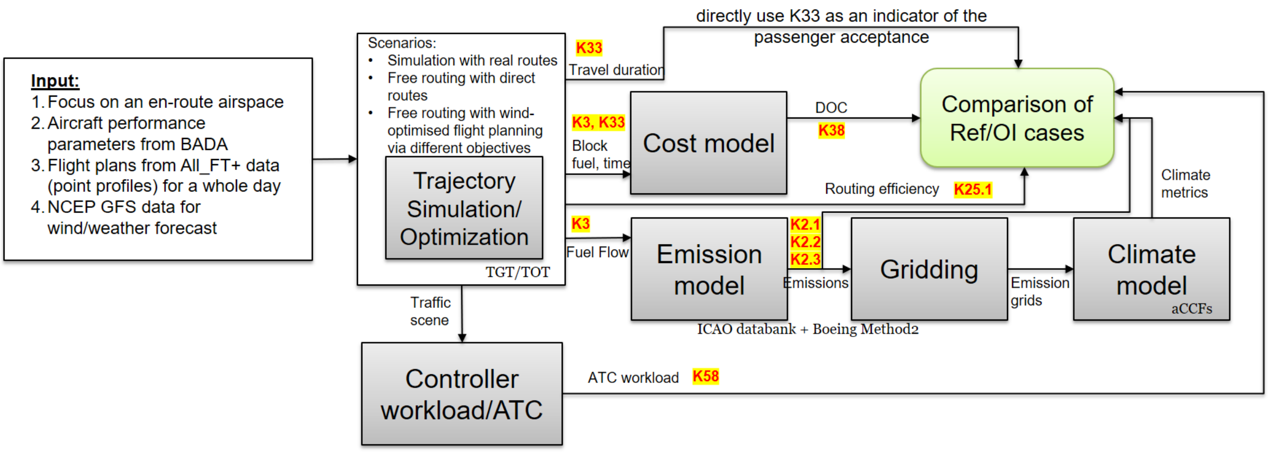


Figure 15. Model workflow for OI of "Free routing and wind-optimised flight planning in high-complexity airspace"

We focus on a representative day to implement the OI. The day is defined as one of the representative days specified in the OI of Flying low and slow to improve the comparability between different OIs and present generalizable results. The representative day (December 11th, 2018) has the most frequent weather type for the winter season in 2018 and captures the frequent patterns for this season [11]. The flight plans of all aircraft operating in the focused airspace during this day are obtained from the point profiles in ALL_FT+ dataset [33]. The wind forecasts are obtained from the

NCEP GFS (National Centers for Environmental Prediction -Global Forecast System) data in which the forecasts are presented for 6-hour periods. The last input for the simulation environment is the set of aircraft performance parameters from the BADA4 (Base of Aircraft Data). One of the most frequent aircraft types operating in the focused airspace, B737-800, is defined as representative aircraft to simulate the traffic. Four different scenarios are prepared to analyse the OI. The scenarios are simulated via the Trajectory Generation Tool (TGT) and Trajectory Optimization Tool (TOT). The details of TGT and TOT have been presented in Deliverables D2.2 and D2.3 [10][11]. In summary, the TGT simulates the motion of aircraft by following the paths between specified waypoints in the flight plan, whereas the TGT generates an optimised trajectory between initial and destination waypoints according to the defined objective by considering the wind information. A baseline scenario in which aircraft fly according to real flight plans is simulated to create the ground truth. In the first case study, the fixed air traffic service routes or intermediate waypoints in the flight plans are removed, and the free routing concept is implemented by defining the shortest paths between entry and exit points in the airspace as the preferred routes. Both the second and third case studies generate optimised trajectories between entry and exit points via the TOT instead of using the shortest paths. Whereas the objective function in the second case study consists of the weighted sum of travel duration and fuel consumption, the third case study prioritises reducing the non-CO_2 emissions by also aiming to decrease the fuel consumption and travel duration. After obtaining the trajectories in the defined scenarios, a set of KPIs is calculated using these trajectories to analyse the OI. The assessed KPIs are listed as the travel duration, fuel consumption, CO_2, NO_x, H_2O, added flight distance (or routing efficiency), conflict probability, ATC workload (via complexity score), direct operating cost, and ATR20.

Results

A. Assessment of climate KPIs

According to the defined scenarios, the simulation and optimization tools generate the flown trajectories that consist of the latitude, longitude, altitude, speed, and fuel consumption. The emission model presented in D2.3 [11] uses the obtained trajectories to calculate the released emissions in the baseline scenario and case studies. After the gridding process, the emission maps and trajectory information are utilised by the algorithmic climate change functions (aCCFs) to calculate the ATR20. The climate KPIs that are evaluated in this OI are CO_2, NO_x, H_2O, and ATR20. The calculated climate-related KPIs for the predefined scenarios are presented in Table 21.

The results show that the free routing concept in the high-complexity airspace has the potential of reducing all emission species and ATR20. The amount of reduction can be changed, depending on the implementation strategy. The greatest reduction potential is in Case 3, because the objective function in the wind-optimised trajectory planning in Case 3 prioritises the reduction of non-CO_2 emissions by also containing fuel and time costs. Case 2 has a standard cost function as a combination of time and fuel costs weighted with a cost index (CI). In this case study, the CI is defined as 7 which leads to a reduction of 25.9% in NO_x, 26.2% in ATR20 and 7% in CO_2. By changing the CI, one of the fuel consumption and travel duration can be prioritised. The fuel consumption (or CO_2) can be further reduced by decreasing the CI, but this also leads to an increase in the travel duration. Case 2 corresponds to the situation in which there is a balance between the time and fuel costs. There is no optimization process in Case 1 in which the free routing concept is implemented via shortest paths, but this strategy has also an obvious advantage in terms of reducing emissions.

Table 21. The released emissions and ATR20 for the case studies with the traffic in the focused airspace (EDUU) on December 11, 2018.

KPI	Baseline Scenario	Case 1	Case 2	Case 3	% Change – Case 1	% Change – Case 2	% Change – Case 3
NO_x [kg] (avg. per flight)	11.35	8.29	8.41	7.78	−27%	−25.9%	−31.5%
CO_2 [kg] (avg. per flight)	2564	2363	2383	2332	−7.85%	−7%	−9%
H_2O [kg] (avg. per flight)	1001	923	931	911	−7.85%	−7%	−9%
ATR20 [10^{-8} K]	2.41	1.76	1.78	1.68	−26.9%	−26.2%	−30.4%

The total ATR20 in different altitude levels and time steps for the baseline scenario and the relative changes in ATR20 for case studies are presented in Figure 15. The base case shows a positive ATR20 among all altitude levels and at each time step between 1×10^{-10} K and 13×10^{-10} K. The strongest climate effects from aviation emission occur at 11 km, with lower contributions from the 9 km level and even lower from the 7 km level.

a. When comparing the alternative cases, it becomes apparent that during the whole day climate effects at the 11 km altitude can be reduced.
b. In Case 1 only, an increase of the climate effects at lower levels (7km) becomes apparent, while at the other altitudes a decrease can be noted. The strongest reduction can be observed at 11 km. This might be connected to the free routing concept and flying at lower altitudes.
c. Similar to before, Case2 shows a strong difference from the base case at 11 km. At this altitude level, the climate effect of aviation can be reduced when changing the trajectory with the TOT tool. While the ATR20 is also slightly reduced at the lowest level, there is a small increase at 9 km. This could be connected to the new aircraft flight levels and trajectories.

Case 3, as expected, shows a reduction at all levels. Similar to the other cases, the strongest reduction can be observed during the morning hours at 11 km. The ATR20 is also reduced at 7 and 9 km. This case has the greatest reduction potential when also taking non-CO_2 effects into account.

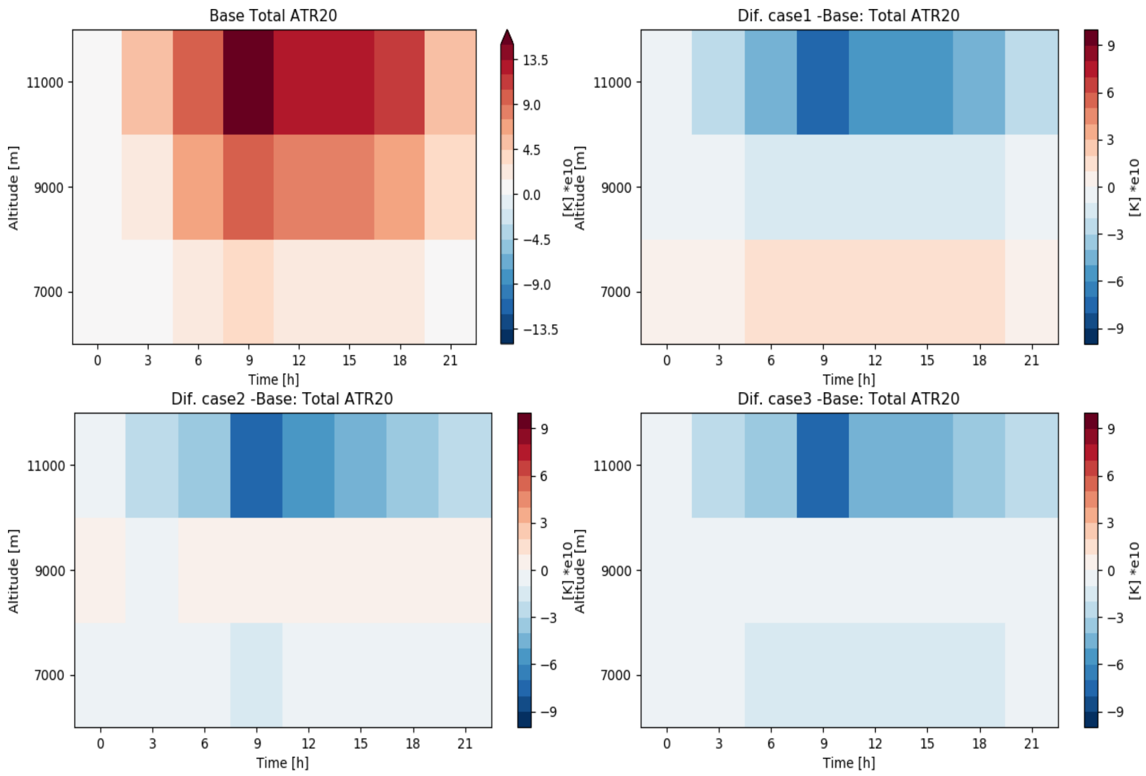


Figure 16. The total ATR20 in different altitude levels and time steps for the baseline scenario, and the relative changes in ATR20 for the case studies

B. Assessment of non-climate KPIs

The non-climate KPIs that are evaluated in this study are the travel duration, fuel consumption, flight distance, direct operating cost, number of conflicts per flight hour, and ATC complexity score. These KPIs are used to assess the operational, technical, economic, and safety aspects of the OI. And, the impacts of the OI on the main stakeholders which are airlines, air traffic controllers, and passengers are analysed. The calculated values of listed KPIs for the baseline scenario and three case studies are given in Table 22.

Table 22. The calculated non-climate KPIs for the case studies with the traffic in the focused airspace (EDUU) on December 11, 2018.

KPI	Baseline Scenario	Case 1	Case 2	Case 3	% Change – Case 1	% Change – Case 2	% Change – Case 3
Travel Duration [sec] (avg. value per flight)	1102	1096	1086	1142	−0.6%	−1.5%	3.6%
Fuel Consumption [kg] (avg. value per flight)	814	750	757	741	−7.85%	−7%	−9%
Flight Distance [km] (avg. value per flight)	248.1	243.9	249.4	249.2	−1.68%	0.53%	0.43%

Direct Operating Cost [$] (avg. value per flight)	1181	1130	1130	1147	-4.3%	-4.3%	-2.9%
Number of Conflicts per Flight Hour	0.1349×10^{-3}	0.1114×10^{-3}	0.1188×10^{-3}	0.1204×10^{-3}	-17.4%	-11.9%	-10.7%
ATC Complexity Score (VDIF + HDIF + SDIF)	0.05003	0.0385	0.0499	0.0607	-22.9%	-0.1%	21.3%
VDIF (hours of vertical interactions per flight hour)	0.0119	0.0085	0.0110	0.0121	-	-	-
HDIF (hours of horizontal interactions per flight hour)	0.0379	0.0299	0.0359	0.0388	-	-	-
SDIF (hours of speed interactions per flight hour)	0.00016	0.85×10^{-4}	0.0029	0.0096	-	-	-

<u>Operational and Economic Assessment</u>

The travel duration, fuel consumption, flight distance, and direct operating cost are used to assess the operational and economic impacts on the airlines. The travel duration and fuel consumption for each flight in the traffic are direct outputs of the trajectory generation and optimization processes. The flight distance corresponds to the number of kilometres travelled by aircraft and can be directly calculated using the trajectory obtained from the simulation. The Direct Operating Cost (DOC) is presented as a combination of the fuel cost and other variable costs that depend on the travel duration based on the FAA's study [36]. The jet fuel price data is obtained from IATA's website [38]. An estimated average value of fuel cost (in the unit of $ per kg) is generated by using the data during 2018 and adding fuel taxes. Other variable costs that depend on the travel duration (in the unit of $ per hour) are obtained from the document [36]. In this way, the impacts of the travel duration and fuel consumption on the direct operating cost are considered.

The free routing with any of the defined planning strategies has the potential of reducing fuel consumption by at least 7% as presented in Table 20. Although the fuel consumption, non-CO_2 emissions and ATR20 are further decreased in Case 3, it leads to a 3.6% increase in the travel duration. A small increase in the flight distance is also observed in Case 2 and Case 3. The simultaneous increase in both travel duration and flight distance for Case 3 shows that the aircraft fly slower to achieve further improvement in reducing non-CO_2 emissions. Both Case 1 and Case 2 lead to a 4.3% reduction in the direct operating cost, whereas a smaller reduction is obtained in Case 3. The results show that the additional direct operating cost associated with the increased travel duration in Case 3 is compensated by the cost reduction in fuel consumption. The free routing with one of the predefined planning strategies brings advantages to airlines. But, Case 3 should also be compared with Case 2 to analyse the cost of using non-CO_2 centralised planning with respect to the current aviation practices. When compared with Case 2, Case 3 has a 1.5% additional direct operating cost for a further decrease in NO_x by 5.5%, ATR20 by 4%, and CO_2 by 2%.

<u>ATC Workload and Safety Assessment</u>

The number of conflicts per flight hour can be directly calculated using the obtained trajectories. The metric is obtained by dividing the total number of conflicts during the day by the total flight hours. Another evaluated KPI is the complexity score. ATC workload is measured using the complexity score proposed in the study [39]. It is proposed to quantify the complexity experienced by an en-route controller using a set of complexity indicators that capture the external factors that affect the ATC workload. The complexity indicators are defined as the potential vertical interaction (VDIF), potential horizontal interaction (HDIF), and potential speed interaction (SDIF). The VDIF captures the potential interactions between climbing, cruising, and descending aircraft. The HDIF and SDIF assess the potential interactions based on the aircraft headings and speeds, respectively. The sum of these three indicators is presented as the ATC complexity score. Rather than focusing on the actual interactions, the indicators present the probability of interactions originating from the traffic flows. This is achieved by using a grid structure that divides the airspace into 4D cells with the dimension of $20\,NM \times 20\,NM \times 3000\,ft \times 1\,hour$. And, the interactions in each cell are calculated by considering the simultaneous presence of two aircraft in the same cell in different flight phases or with different headings/speeds. For example, the HDIF is calculated as follows:

$$T_k = \sum_{i \in cell_k} t_i \text{ is the sum of the time flown in cell } k \text{ (in one hour)}$$

$$H_k = \sum_{i \in cell_k} \left(\sum_{j \in cell_k \text{ } i \text{ and } j \text{ have different headings}} t_i \cdot t_j \right) \text{ is the "hours of horizontal interactions" in cell } k$$

$$HDIF = \frac{\sum_{Days} \sum_{Cells} H_k}{\sum_{Days} \sum_{Cells} T_k}$$

The VDIF and SDIF can also be calculated similarly. Further information and the detailed calculation procedure can be found in the study [39].

The conflict metric and complexity score are calculated for the defined scenarios and the results are presented in Table 20. The number of conflicts per flight hour is reduced in every case. Although the greatest reduction of 17.4% is obtained using the shortest paths, the wind-optimized planning solutions have approximately 11% reduction in the conflict metric. Therefore, the free routing with any of the defined planning strategies does not jeopardise safety. However, things get a little more complicated when considering human performance. The ATC complexity score and its components are presented for each scenario in Table 20. When the shortest paths are preferred which correspond to Case 1, the horizontal and vertical interactions are decreased and this leads to a 22.9% reduction in ATC complexity. However, when the trajectories are optimised in Case 2, this leverage is lost. There is almost no improvement in Case 2. Moreover, there is a 21.3% increase in the ATC workload in Case 3. The main reason for this increase in ATC complexity is the escalated speed interactions (SDIF). Because of prioritising the minimization of the NO_x emission, Case 3 generates monotonically decreasing speed profiles that lead to higher potential speed interactions (SDIF). Although the ATC complexity is at a manageable level, the monotonically decreasing speed profiles increase the ATC workload.

Human Performance Assessment

The following table (table 23) collects the changes on Human Performance Arguments areas (Roles and Responsibilities, Human and Systems, Teams & Communication, HP Related Transition Factors) introduced by the free routing and wind-optimised flight planning concept. The identification of relevant arguments is the first step for HP assessment.

Table 23. Description of change

HP Argument branch	Change & Affected Actors
1. Roles & Responsibilities	
1.1. Roles & Responsibilities	The roles impacted by this solution are the ATC, the Pilots, and the Airlines.
1.2 Operating methods	Normal operating methods are expected to remain the same, while abnormal and degraded way to operate may change as the ATC will have less control on the flight plans, therefore it might face an increase in workload in high volume of airspace.
1.3 Tasks	The task of the ATC will be same. But there could be more routes to assess to ensure the safety if the free routing concept is implemented in a high volume of airspace. Depending on the airspace volume and traffic demand, additional decision support tools could be required. Also, the pilots' task will not change. However, an enhanced communication between pilot and aircraft dispatcher could be required to implement the dynamic flight planning. Finally, airlines will have more possibilities to optimise their routes depending on specific needs. Nonetheless, an enhanced flight planning strategy and weather prediction service could be required to improve the performance.
2. Human & System	
2.1. Allocation of tasks (Human & System)	The performance of the technical system will not require modification to allow the introduction of the free routing and wind-optimised flight planning concept. Nonetheless, if the free routing concept is implemented in a high volume of airspace with a high traffic demand, improved conflict detection and resolution tools could be required to perform the separation provision tasks.
2.2. Performance of Technical System	To be assessed at a later stage.
2.3. Human-Machine Interface	To be assessed at a later stage.
3. Team & Communication	

3.1. Team Composition	The FREE concept won't introduce changes in team composition. No new role will be required to carry out the tasks.
3.2. Allocation of tasks	The task allocation will remain the same.
3.3. Communication	Intra- and inter-team communication may change after the introduction of FREE. The workloads of pilot, aircraft dispatcher, and controller could be increased due to the increased communication caused by dynamic flight planning strategy implementation.
4. HP related transition factors	
4.1. Acceptance & Job satisfaction	ATC may be the human actor more reluctant to accept the change introduced as it will be the one who will face an increase in workload.
4.2. Competence requirements	No changes in competence requirements are foreseen.
4.3. Staffing requirements & staffing levels	No changes staffing requirements and staffing levels are foreseen.
4.4 Requirement and Selection	No changes in staff requirements and selection are foreseen.
4.5 Training Needs	Training needs may be required whether if the free routing concept is implemented in a high volume of airspace with a high traffic demand

The Consortium identified two high-level hypotheses that guided the high-level validation of the change introduce by FREE:

a. This change will have a large impact on ATC controllers, especially in a high volume of airspace with a high traffic demand and when a dynamic flight planning strategy is implemented.
b. Improved conflict detection and resolution tools could be required to perform the separation provision tasks.

In order to assess the impact of the *free routing and wind-optimised flight planning* concept on ATC, the ClimOP Consortium held an interview with one Air Traffic Controller (ATC) from ANACNA, the Italian National Association for ATC. From the exchanges we had with the ATC, free routing has appeared to be an operational concept already in use in the ATM. The proposed combination with a dynamical flight planning that considers wind fluxes will be the changing factor.

The Free Routing Aerospace (FRA) appears to be used in all the EU member states [1]. However, the 'COMMISSION IMPLEMENTING REGULATION (EU) 2021/116' requires the final FRA, including cross-border FRA with at least one neighbouring state and FRA connectivity with TMAs, to be implemented by 31 December 2025. The extension of FRA to the EU level implies the need to optimise "points of exchange" between neighbouring areas. Now traffic tends to follow past trajectories, but the concept must consider that flows may change in the future. Moreover, introducing FRA at the EU level will require improving the exchange of flight data between ANSPs following a line instead of a trajectory of points (i.e. through flexible points). The ATCo also suggested taking into account the need to handle military areas, which usually require circumnavigation.

From the ATCO perspective, peak traffic hours will produce a limited impact on ATC performances as traffic will move from points to points instead of airways. FREE does not represent an issue until the pilots get to the edge between the two sectors. In those situations, ANSPs should agree on whose responsibility it is. Apart from that, the ATCO claimed traffic management does not create an additional workload for them. It should be also noticed that ATCOs make use of a medium-term conflict detector (MTCD), a semi-automatic tool for conflict management, which confirms our second hypothesis about the need for a tool to support ATC.

ATCOs will not be impacted by FREE also because the flight planning happens at the strategic level. Therefore, there will be plenty of time to assess if the proposed trajectory has problems passing through busy areas or if any restrictions are necessary. No shared management, optimised by other parameters (like wind), appears to be in place on short-haul flights. Nonetheless, some companies employ a Cost Index that considers different parameters to optimise the flight trajectories. These indicators could include information on air currents in certain geographical areas in order to optimise flight performance.

The Airline's perspective was grasped thanks to the IATA review of the operational improvement. Airlines were more concerned by the impact this operational improvement produces on costs than on their performance as human actors.

In conclusion, ATC seems to be impacted only in specific cases, mainly depending on the coordination between ANSPs. Further research will be needed to explore in more detail what changes in ATC operation might be needed to make room for the introduction of free routing and wind-optimised flight planning.

Passenger Acceptance

The main factors that have a direct impact on the passengers are the ticket price and travel duration. There is no increase in direct operating cost in any implementation strategy, so we may assume that the ticket price will not be increased by implementing the OI. However, this study is limited to the direct operating cost. Further assessment should be performed by considering all costs in addition to the direct operating cost to make a clearer conclusion. An assessment should also be done using the travel durations. Although the travel durations are decreased in Case 1 and Case2, Case 3 leads to a 3.6% increase in the travel duration. This increase could also be considered acceptable. A survey on passenger acceptance has been performed to further investigate passenger acceptance, and the results are presented in Appendix C. It is obtained that 64.7% of participants are in favour of increasing flight time by 20% on the short-haul for reducing climate impact, while 10.6% of participants are against a 20% increase in flight time.

C. Uncertainty estimate

The main uncertainty sources that have an impact on the calculations are defined as initial mass uncertainty, performance model uncertainty, wind uncertainty, emission modelling uncertainty, and climate modelling uncertainty. The initial mass, performance model, and wind uncertainties define the overall trajectory uncertainty. The emission modelling uncertainty and climate modelling uncertainty only have an impact on the emissions and ATR20, respectively.

The initial mass of an aircraft is estimated using the calculated fuel consumption and an average passenger load factor. Because there is no available data for the real passenger load factor of each specific flight, the average load factor in 2018 is used to specify the load factor as 0.82 for all flights. To define the impact of the initial mass uncertainty on the fuel consumption, the traffic is simulated with $\mp 5\%$ deviation in load factor. It is observed that 5% load factor uncertainty results in $\mp 1.5\%$ deviation in fuel consumption. Similarly, wind uncertainty is also assessed via simulations. The wind forecast error is modelled as a normal distribution with zero mean and standard deviation of $3\ m/s$ as estimated in the study [40] using real data. The simulation results show that this forecast error leads to the uncertainty in travel duration with a standard deviation of 1.2% and the uncertainty in fuel consumption with zero mean and standard deviation of 0.5%. Another source of uncertainty can be presented as the aircraft model based on BADA4. BADA4 provides an accurate model for nominal aircraft performances with respect to manufacturers' performance data. However, in reality, individual aircraft of the same type perform differently. As an airframe or engine ages, aerodynamic and performance deterioration tends to increase fuel burn. Although the original performance is largely restored during overhauls, a real aircraft can burn additional fuel up to $5 - 7\%$ with respect to the nominal performance in the worst-case scenario [41, 42]. Therefore, the real fuel consumption of some aircraft in the traffic can be higher than the obtained values in the simulation environment. However, the impact of the performance deterioration on the obtained percentage fuel reductions is negligible because the performance deterioration leads to scaling the fuel consumption of a specific aircraft in different scenarios with the same constant. The climate impact assessment is achieved via aCCFs in which there are also uncertainties arising from model development and adjustment via scaling factors. Further information about the climate modelling uncertainty can be found in the section on climate-optimised flight planning.

D. Comparability of the results with the other OIs

The OI is implemented by focusing on a high-complexity en-route airspace (EDUU) in ECAC area. Although the benefits obtained from the implementation of the free routing and wind-optimised flight planning are not specific to the focused airspace, we cannot directly predict the full mitigation potential of the implementation of the free routing concept in ECAC area by scaling up the results. However, the mitigation potential arising from the implementation of the OI in the corresponding airspace can be easily compared with the other trajectory-related OIs by assessing the absolute numbers and relative reductions. The results for this OI are obtained for a representative day that can be scaled up to the full season and also used in the OI of flying low and slow to improve comparability. The OI is implemented using the flight plans of all aircraft operating in the focused airspace during the representative day. On this day, 17% of all flights operating in ECAC area use the corresponding airspace. The modelling approaches, temporal and geographical scope make all trajectory-related OIs comparable. The OI can be directly compared with the other trajectory-related OIs.

E. Applicability of the OI

There is no major issue that can be faced when applying the free routing concept with the defined planning strategies. But, the improvements in two different infrastructures can help to increase the benefits obtained from the concept. An advanced wind/weather forecast system can help to improve the performance of wind-optimised flight planning. There is already an attempt to create such a system. The global Aircraft Meteorological DAta Relay (AMDAR) program has been initiated by WMO (World Meteorological Organization) and its members in cooperation with aviation partners [44,45]. The AMDAR observing system uses predominantly existing aircraft onboard sensors, computers, and communications systems to collect, process, and transmit meteorological data to ground stations. The obtained information is provided to meteorological agencies, computerised weather prediction systems, and involved airlines. These in turn support the generation of forecast and weather service products for aviation. In this way, the airlines can obtain more accurate wind/weather information. Furthermore, an improved communication system can also enhance the system performance when a dynamic flight planning strategy is implemented based on the updated forecasts. The communication between the dispatcher and pilot can be ensured via the existing Aircraft Communication and Reporting System (ACARS) datalink unit. However, the improved communication between the pilot and ATC with an advanced system such as the controller-pilot data communication (CPDLC) can help to improve the performance in a dynamic flight planning setting.

Conclusions

Overall, the OI has a significant potential to reduce fuel consumption, ATR20, CO_2 and non-CO_2 emissions. By prioritising the reduction of non-CO_2 emissions in the objective function of the planning algorithm, further reductions can be obtained in environmental impact with additional cost in travel duration and ATC complexity. In the focused airspace, the free routing concept showed an overall reduction potential of around $7-9\%$ in fuel consumption and CO_2 and $26-31\%$ in NO_x and ATR20. Whereas the implementation of the free routing with the wind-optimised planning by prioritising the time and fuel cost resulted in a 4.3% decrease in the direct operating cost, the non-CO_2 centralised planning led to a 1.5% cost increase with regards to the cost-prioritised planning. Although the latter planning strategy improved CO_2, NO_x and ATR20 reduction by around 2%, 5% and 4% respectively, it caused an increase of 3.6% in travel duration and 21.3% in ATC complexity. Additional burdens in the latter case may limit the implementation of this strategy. Because of the 19% increase in ATC complexity in the latter case originated from the escalated speed interactions as a result of the monotonically decreasing speed profiles, this additional ATC complexity can also be mitigated by implementing the decreasing speed patterns in a graded manner that also sacrifices a portion of the improved CO_2 and NO_x reduction.

A.3 Climate-optimised flight planning

Climate-optimised flight planning (CLIM) aims to identify alternative flight paths that have a lower overall impact on climate by avoiding regions of the atmosphere that are particularly sensitive to aircraft emissions. In D2.3 we evaluated this OI by identifying climate-optimised aircraft trajectories in an expanded air traffic management (ATM) system based on algorithmic climate change functions (aCCFs) in the European airspace. A comprehensive case study was conducted for the European airspace, examining both individual mitigation gains and combined mitigation gains based on individual flight analyses considering CO_2 and non-CO_2 effects comprising contrail-cirrus, NO_x-induced effects on ozone and methane, as well as water vapour direct effects. Analysis shows that mitigation potentials between individual city pairs vary depending on the atmospheric characteristics of the airspace (flight corridor). Under a systems approach, an efficient implementation could rely on establishing a common mitigation potential threshold, when selecting alternative aircraft trajectories. This results in a relationship between the achievable reduction in climate impacts relative to associated fuel penalty or direct operating costs. By applying this common threshold to individual flights, the flights with higher mitigation potential contribute more to the mitigation effort (since they provide "cheap mitigation"), while the flights with low mitigation potential contribute less (since they only provide "expensive mitigation"), resulting in efficient implementation. Results from such a one-day case study were analysed in Phase 1 and used data which has been published in Matthes et al. (2020) [15] and Lührs et al. (2021) [43]. The case study refers to a winter situation on December 18, 2015, characterised by a contrail region over central European airspace on that day.

In this second phase, the CLIM OI is examined for specific intercontinental city pairs for a case study in the year 2018 while introducing a scenario with high non-CO_2 effects covering geographic regions where large uncertainties in terms of the climate impact of aviation emissions prevail. For the reference simulation an updated estimate of aCCFs was used, as described in a scientific paper3, especially exploring to what extent the strength of the non-CO_2 effects (compared to the CO_2 climate effects) influences the resulting trajectory optimization. A comparison between the reference case and this “high non-CO_2 effects" scenario has been conducted.

Methodology

In this phase, the CLIM OI uses an updated formulation of aCCFs to describe the climate impact of CO_2 and non-CO_2 effects in trajectory optimization experiments. Overall, the modelling chain for climate-optimised flight planning relies on the provision of spatially and temporally resolved information on the sensitivity of the atmosphere to aviation emissions to enable trajectory planning and optimization from a climate impact perspective. Considering this climate impact information in the overall objective function (mathematical cost function) of the trajectory optimization allows us to evaluate and identify alternative trajectories which have a lower climate impact.

In this deliverable we investigate the climate impact on a selected day based on real atmospheric data. The study also presents mitigation potentials of climate optimised trajectories for night flights as has been shown in previous studies. Furthermore, we want to explore the sensitivity by using scaled non-CO_2 aCCFs (NO_x, H_2O, Contrails) within the range of uncertainties. Therefore, we scaled the non-CO_2 aCCFs by one order of magnitude (factor 10).

The same modelling workflow of this OI that has been presented in D21, D2.2 and D2.3 was used. A summary of the workflow is shown in Figure 17.

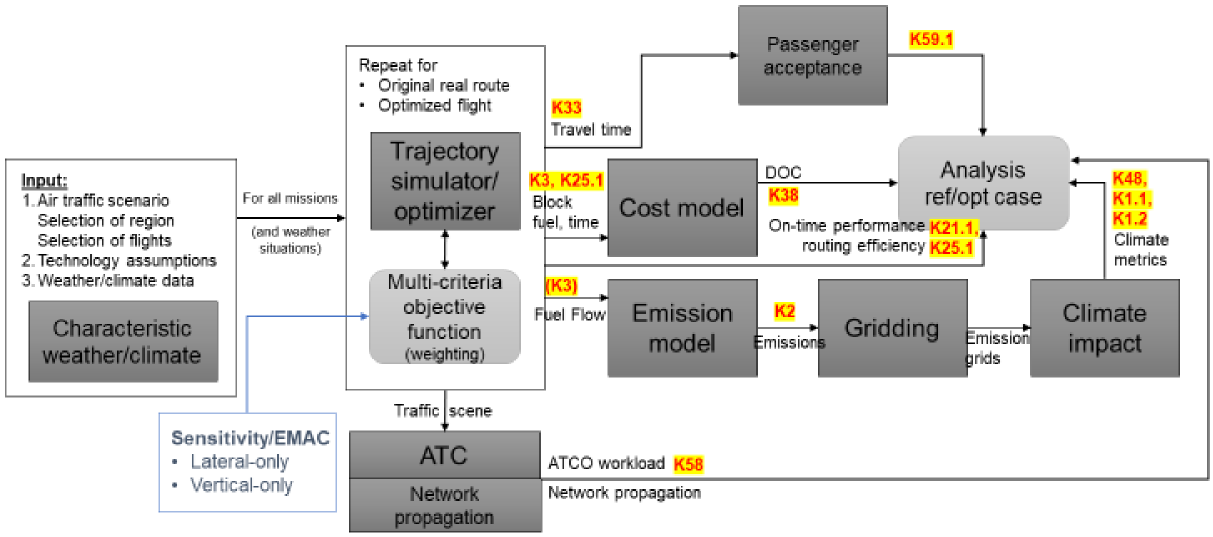


Figure 17 Modelling workflow for climate optimised flight trajectories

To provide the meteorological data for the OI CLIM simulation, we use ECMWF meteorological data (3-hourly 0.25x0.25° ERA5 reanalysis data). In the previously published one-day case studies [15], ERA-5 reanalysis data were used to estimate mitigation potentials based on a realistic representation of real atmospheric conditions as they existed on that specific (historical) day. Such numerical reanalysis model data also rely on assimilation of observational data to improve numerical weather prediction with observations. Another option for the CLIM OI assessment would be to use historical forecasts to simulate and identify alternative trajectory options using only knowledge available prior to departure (historical forecast). This means that no observational data would be incorporated into the meteorological data. In this study we use reanalysis data, which has also been used in the development of climate change functions within the EMAC global chemistry-climate model. This general circulation model can be run in a "nudged" mode, using specified dynamics from real-world situations (meteorology) as boundary conditions resulting in meteorological situations comparable to the situation that prevailed on a given day.

Simulations are performed with an air traffic sample on the selected winter day using realistic atmospheric data in terms of temperature, pressure, wind and relative humidity. The specific day was selected to be the same as for the LOSL OI The 11th of December was selected because the classification of the DWD (Deutscher Wetterdienst) over Germany shows a typical weather pattern in terms of temperature and humidity profile [14]. We focus our analysis on the main aircraft types for long-haul flights to/from the ECAC area and short-haul and medium-haul flights within the ECAC area according to the available seat kilometres (ASK) covered. Therefore, we select A330-243 for the long-haul flights departing from Europe. All flights had their departure time at midnight, in order to consider night-time contrails in this optimization.

The Trajectory Optimization Module (TOM) which uses optimal control techniques in order to determine climate optimised aircraft trajectories, is used similarly to the previous phase to determine fuel-optimal trajectories as well as alternative trajectories. Trajectory output of position, altitude, time increment, atmospheric background conditions, and fuel flow is used to calculate emission fluxes for each flight segment. CO_2 and water vapour emissions are linear to fuel burn, nitroxides (NO_x) are modelled using the DLR fuel flow correlation method [12]. Using the algorithmic climate change functions (aCCFs) for CO_2, ozone, methane, water vapour and contrail-induced cirrus clouds, we can calculate the climate effects for each species individually. The aCCF by the nature of their implementation via meteorological key parameters, account for seasonal and annual variations in the meteorology together with latitudinal effects on solar radiation and atmospheric conditions (temperature, humidity, and potential vorticity). Total climate effects of individual flight segments are aggregated along the entire flight path in order to obtain the total climate effect for each individual flight. For more details, please refer to the description of the aCCFs in [13], which were used in a slightly adapted from within this study.

To compute the ATR20, we used aCCFs (educated guess, BAU scenario) of NO_x-induced effects, contrails, water vapour and CO_2, similar to the aCCFs used in the FlyATM4E case studies of the year 2018 [13][16], which will be presented in a concept paper recently submitted by Matthes et al. Besides ATR20, we analyse performance indicators flight time and fuel burn, and quantify associated penalties. Impacts on non-climate KPIs such as direct operating costs, safety, and passenger acceptance are estimated based on simulation results related to flight time, fuel consumption, and selected flight levels.

Results

Assessment of climate KPIs

Table 24 shows the results for a single mission from London (United Kingdom) to New York (United States) and Frankfort (Germany) to Toronto (Canada) on 11 December 2018. For LHR-JFK, the cost optimal flight departs at midnight and takes approximately 7 hours and 19 minutes. The ATR20 value for the cost-optimal reference case is about 2.7 nK, which is mainly due to a 63% NO_x and 20% contrail effect. The CO_2 ATR20 share with only 10% plays a subordinate role in this metric. However, a significant ATR20 reduction can be achieved by a small increase in fuel consumption and flight time. An increase of 0.2 t fuel results in a lower NO_x ATR20 contribution to the total ATR20 and a reduction in total ATR20 of about 0.1 nK. Increasing the fuel use even further to up to 1.6 t more (~5%), the NO_x induced ATR20 is reduced even more, with a total ATR20 reduction of about 0.2 nK. For the flight to Toronto, an ATR20 reduction of 0.9 nK with a 1 t fuel increase can be achieved by avoiding contrail forming areas.

Figure 18 illustrates the proportion between the different climate effects and especially shows the difference between CO_2 effects and non-CO_2 effects for these short-term metrics (20 years horizon). While the impact of CO_2 and H_2O does not significantly increase, and the contrails impact gets significantly reduced for the FRA-YYX flight. For this flight, NO_x gets more dominant at lower total ATR20 values while the reverse is true for the London - New York flight.

Table 24: Changes in major KPIs compared to reference scenario (cost-optimal) for single climate-optimized night flights on Dec 11th, allowing a fuel penalty of a range from 0.1% to 5% for a set of climate metrics.

		Fuel Penalty	Fuel [t]	Flight Time Penalty	Flight Time [h]	F-ATR20 Reduction	F-ATR20 [K] $\times 10^{-9}$	F-ATR20 $CO_2/H_2O/NO_x$/Cont [%]
LHR - JFK	Cost optimal	-	34.55	-	7.31	-	2.7	9/7/63/20
	Climate optimized	+ 1 %	34.75	+ 1,2 %	7.40	- 2,6 %	2.6	9/7/62/21
		+ 2 %	35.09	+ 3,8 %	7.59	- 2,6 %	2.6	9/7/57/27
		+ 3 %	35.60	+ 5,7 %	7.72	- 7,5 %	2.5	10/6/57/26
		+ 5 %	36.14	+ 7,2 %	7.84	- 10,9 %	2.4	11/6/58/25
FRA - YYZ	Cost optimal	-	54.67	-	7.60	-	6.2	6/4/61/29
	Climate optimized	+ 0.1 %	54.74	+ 0,1 %	7.61	- 4,5 %	5.9	6/4/63/26
		+ 0.5 %	54.97	+ 0,4 %	7.63	- 9,0 %	5.6	7/4/66/23
		+ 1 %	55.14	+ 0,5 %	7.64	- 11,4 %	5.5	7/5/67/21

		+ 2 %	55.73	+ 1,6 %	7.72	- 14,8 %	5.3	7/4/67/22
SNN - JFK	Cost optimal	-	42,47	-	6,06	-	4,6	7/5/63/26
	Climate optimized	+ 0,2 %	42,54	+ 0,1 %	6,07	- 1,3 %	4,5	7/5/63/26
		+ 1 %	42,84	+ 1,0 %	6,12	- 3,7 %	4,4	7/4/62/27
		+ 1,2 %	42,99	+ 1,3 %	6,14	- 3,8 %	4,4	7/4/61/28
		+ 3 %	43,58	+ 3,4 %	6,26	- 8,9 %	4,2	7/5/64/29
MAD - SJO	Cost optimal	-	55,58	-	10,84	-	5,1	8/3/69/21
	Climate optimized	+ 0,1 %	55,66	- 0,3 %	10,87	- 1,9 %	5,0	8/3/70/19
		+ 0,3 %	55,73	- 0,4 %	10,88	- 6,4 %	4,8	8/3/73/16
		+ 1,6 %	56,51	- 2,5 %	11,11	- 7,4 %	4,8	8/3/71/17
		+ 6 %	58,94	- 9,2 %	11,84	- 12,1 %	4,5	9/3/72/15

Table 25 lists performance indicators of the four Atlantic night flights on 11 December 2018 in the "high non-CO_2 effects" aCCF scenario. The aCCF were scaled to investigate the impact of higher non-CO_2 effects on the flight trajectory optimization. The flight from London Heathrow (United Kingdom) to New York John F. Kennedy International Airport (United States) takes approximately 6 hours and 13 minutes and has a fuel consumption of about 34.3 t for the cost optimal situation. A total ATR20 impact of about 27 nK can be calculated that is dominated by non-CO_2 effects (99%), getting slightly lower when flying on alternative trajectories. The largest contribution to ATR20 originates from NO_x effects, which can also be seen in Fig. 18. Different climate optimised cases are shown for the flight from LHR to JFK, ranging from an ATR reduction from 1.8 nK to 4.7nK with a fuel increase of about 0.5 t to 1.5 t respectively 1% to 5%. All climate optimised cases are mainly focused on reducing the highest contributor NO_x, decreasing the NO_x contribution to the total ATR20 to 60-65%.

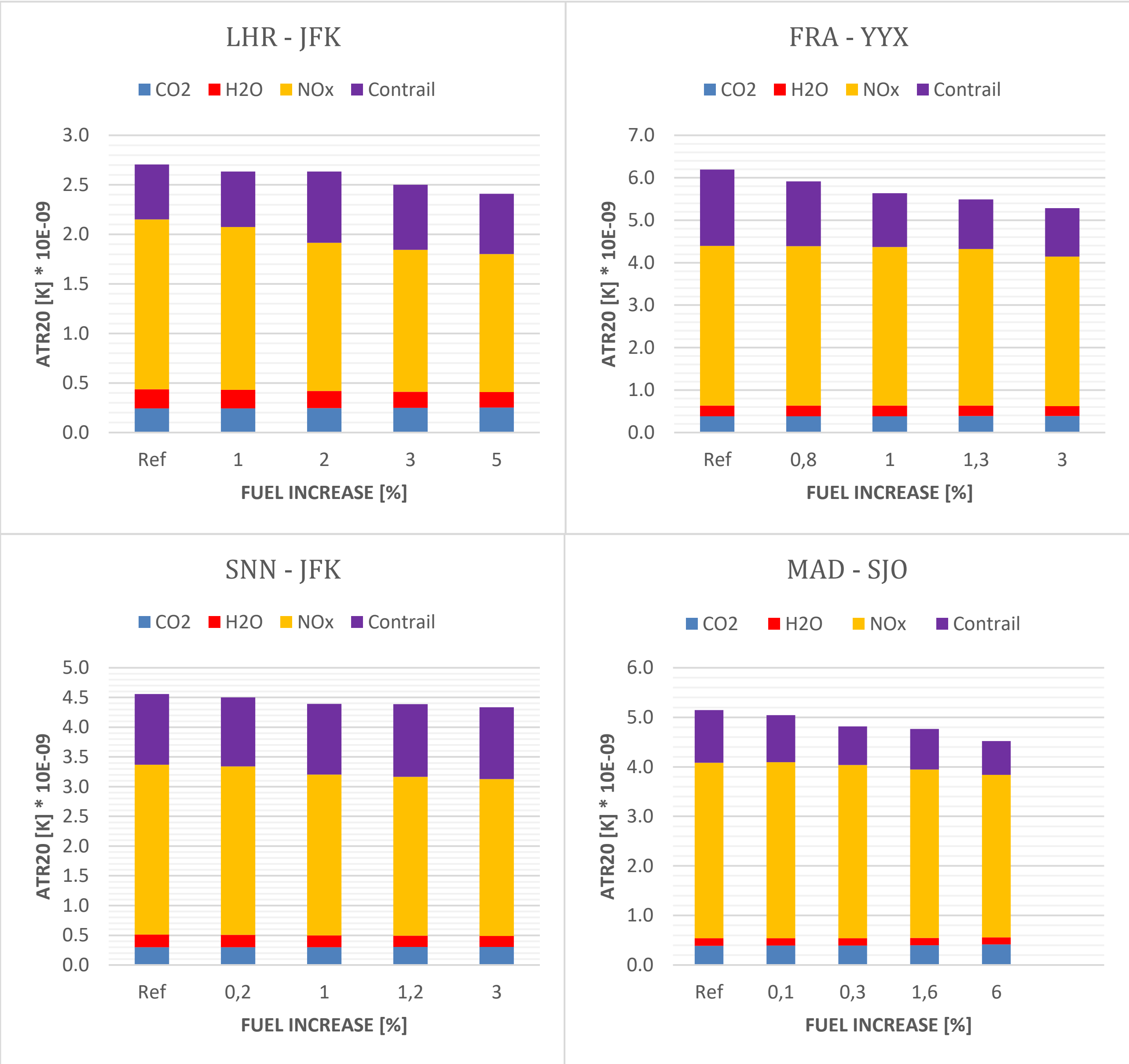


Figure 18. Individual contributions to total climate impact.

In addition to the London – New York flight the analysed 3 Atlantic night flights from Frankfurt to Toronto (FRA-YYZ), Shannon to New York (SNN-JFK) and Madrid to San José (MAD-SJO). All these flights show a high contribution of NO_x to the total ATR20 ranging from 65% to 77% while CO_2 plays only a subordinate role (~1%). Especially the flight in the tropical area to Costa Rica has higher NO_x effects and lower contrail effects (Fig. 19). While the total ATR20 is reduced more and more by increasing the flight time and fuel use, the best mitigation potential per fuel can be already achieved by lower fuel increase of about 1-2%. For example, the route from Shannon to New York (SNN-JFK) has a mitigation potential of about 10.1 pK/(kg fuel) with a fuel penalty of 1%.

Figure 19 illustrates the contribution from individual climate effects to the total climate effect, also illustrating the different strength of CO_2 effects and non-CO_2 effects for these short-term metrics. While the effect of CO_2 and H_2O do not significantly decrease on climate optimised trajectories, the

NO_x-induced forcing is considerably reduced resulting in an overall reduction in total ATR20 by 17%. At the same time contrail climate effect even increases by a small amount.

By comparing the performance indicators in the standard case with the “high non-CO_2 effects” aCCF scenario, we see an increase of total ATR20 by a factor of 10 for the scaled non-CO_2 ACCF simulations. This was to be expected, as the non-CO_2 effects have the potential to play a dominant role over these short-term time horizon metrics (e.g. ATR20). Our analysis shows that the mitigation potential in these cases is higher than for the standard case.

Table 25: Changes in major KPIs compared to reference scenario (cost-optimal) for different single climate-optimized night flights on Dec 11th, allowing a fuel penalty of a range from 0.3% to 5% for a set of climate metrics. For these sensitivity simulations, the non-CO_2 aCCFs were scaled by an order of magnitude (factor 10).

		Fuel Penalty	Fuel [t]	Flight Time Penalty	Flight Time [h]	F-ATR20 Reduction	F-ATR20 [K] × 10^{-9}	F-ATR20 CO_2/$H_2$0/ NO_x/Cont [%]
LHR - JFK	Cost optimal	-	34.32	-	7.16	-	27.4	1/8/70/22
	Climate optimized	+ 1 %	34.81	+ 2,6 %	7.35	- 6,5 %	25.6	1/7/65/26
		+ 2 %	34.97	+ 4,3 %	7.46	- 10,3 %	24.6	1/8/66/25
		+ 3 %	35.40	+ 7,3 %	7.68	- 16,4 %	22.9	1/8/65/26
		+ 5 %	35.88	+ 8,9 %	7.79	- 17,1 %	22.7	1/7/63/29
FRA - YYZ	Cost optimal	-	54.56	-	7.61	-	55.6	1/5/67/27
	Climate optimized	+ 0.8 %	54.99	+ 0,2 %	7.62	- 5,1 %	52.8	1/5/71/23
		+ 1 %	55.06	+ 0,4 %	7.64	- 5,4 %	52.6	1/5/71/23
		+ 1.3 %	55.30	+ 0,7 %	7.67	- 7,6 %	51.4	1/5/71/24
		+ 3 %	56.24	+ 2,6 %	7.81	- 8,2 %	51.0	1/4/68/27
SNN - JFK	Cost optimal	-	42.22	-	6.03	-	45.4	1/5/65/29
	Climate optimized	+ 0.3 %	42.33	+ 0,1 %	6.04	- 1,8 %	44.6	1/5/67/28
		+ 1 %	42.54	+ 0,6 %	6.07	- 7,1 %	42.2	1/5/68/27
		+ 1.7 %	42.96	+ 1,7 %	6.13	- 8,2 %	41.7	1/5/65/30
		+ 2 %	43.11	+ 2,7 %	6.19	- 11,0 %	40.4	1/5/65/29

MAD - SJO	Cost optimal	-	55.30	-	10.77	-	48.5	1/3/76/20
	Climate optimized	+ 0.4 %	55.51	+ 0,6 %	10.83	- 1,4 %	47.8	1/3/75/21
		+ 0.6 %	55.62	+ 0,7 %	10.85	- 5,2 %	45.9	1/3/78/18
		+ 1 %	55.92	+ 1,6 %	10.94	- 5,8 %	45.7	1/3/77/19
		+ 3 %	56.79	+ 4,2 %	11.22	- 8,7 %	44.2	1/3/77/19
		+ 5 %	57.85	+ 6,5 %	11.46	- 8,9 %	44.1	1/3/76/20

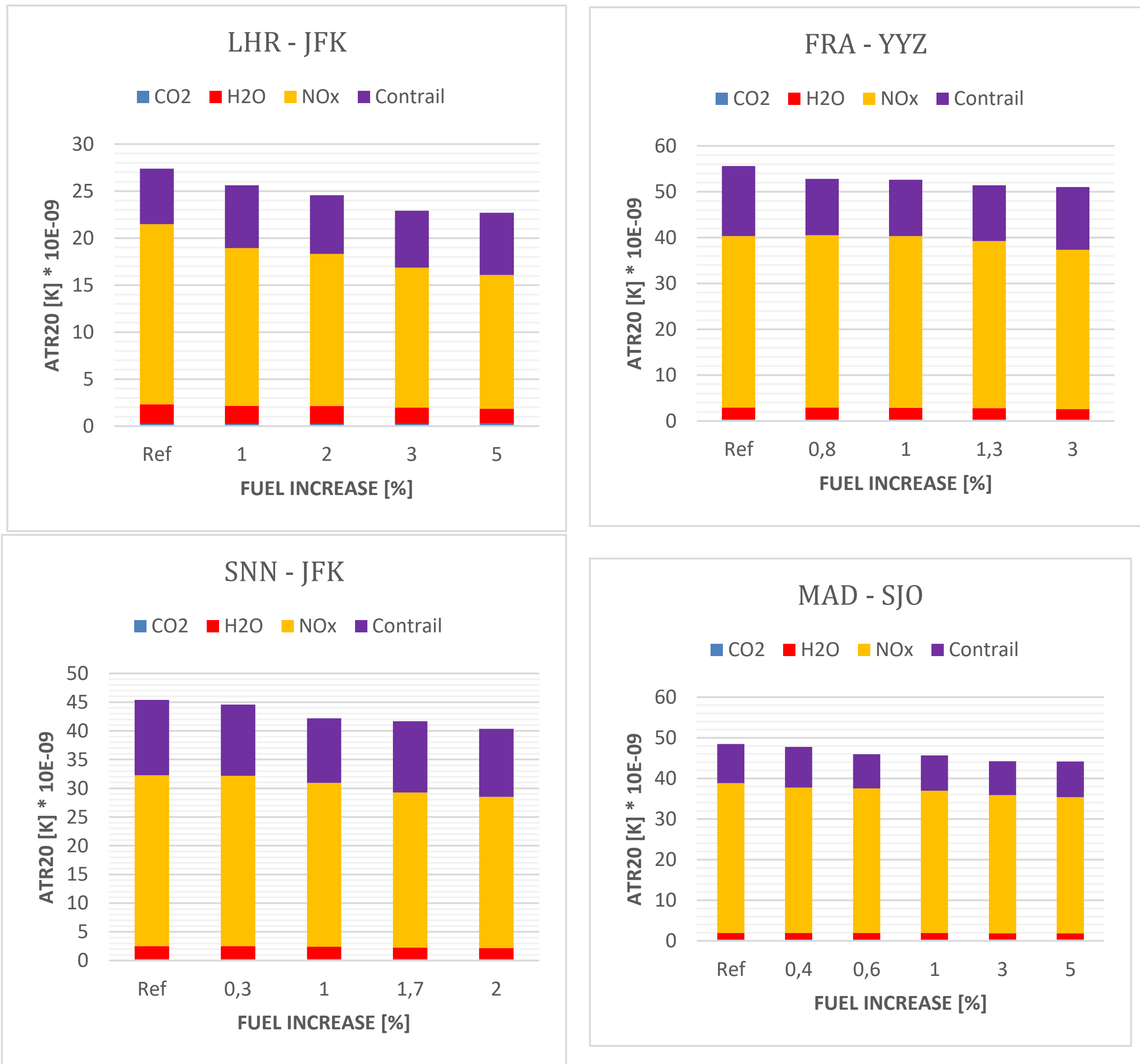


Figure 19. Contribution from individual climate effects to the total climate effect, the non-CO_2 aCCFs were scaled by an order of magnitude (factor 10).

A. Assessment of non-climate KPIs

The assessment of non-climate related KPIs focuses on key stakeholders that are expected to be affected by the implementation of climate-optimised trajectories. Therefore, the analysis focuses on the following stakeholder-oriented KPAs and KPIs:

- Airlines: Fuel consumption, Flight time
- Air traffic control: Air traffic controllers' workload, accident rate (ATM and safety assessment)
- Passengers & Society: Passenger acceptance (Acceptance assessment)

Based on the results and performance assessments of expanded trajectory optimization, a qualitative description of the impact of a CLIM implementation on the different stakeholders is provided, together with a quantitative estimate of the KPIs described.

Economic assessment

Bypassing climate-sensitive regions is primarily associated with an increase of flight time and potentially higher fuel consumption. For the presented alternative solutions an increase of less than 1% up to an increase of several percent has been calculated (see section 2.3). From an airline's perspective, this increases operating cost due to an increase in fuel consumption (EU ETS, CORSIA). Nevertheless, small adjustments to the flight route with a small increase in fuel costs and flight time could significantly reduce the impact on the climate. We restricted the fuel and time penalties to certain limits as discussed in the previous section, with a range of 0.2-5 % fuel and time increase (table 25). It was also shown that the climate mitigation potential for fuel usage is higher for smaller fuel penalties.

ATM and safety assessment

In this section we repeat concerns of airspace users which are raised in the context of an implementation of climate-optimised trajectories. We recognize that adding more information to a flight plan increases complexity. However, the analysis currently underway also indicates that complexity is highly dependent on the specific synoptic weather situation. In our view, greater knowledge of such mechanisms and weather patterns can add further detail to this topic. Climate-optimised flight trajectories affect airspace use and have consequences for airspace users: directing the same volume of traffic into reduced airspace means over-concentration of traffic in the same volume of airspace, which has implications:

- It is important to note that airlines flying in the EU were already experiencing a capacity shortage in the European ATM network before the pandemic. New constraints and restrictions in the airspace goes against capacity optimization, as reducing the available airspace will accentuate the capacity crunch problem once the traffic levels are restored [38].
- Air Traffic Control Workload: The change in available airspace would result in increased air traffic control workload at the air navigation service provider, which would have a cascading effect on the need for additional air traffic control personnel. New air traffic control work methods and procedures, and possibly system upgrades, would need to be implemented in air carrier OCCs to address the potential constraints of not approaching/exiting the sensitive areas, which would result in an increase in OPEX for airspace users as systems would need to be modified/upgraded accordingly.
- Additionally, increasing flight times, and/or not flying the preferred flight levels, would worsen the performance of the European ATM Network, making it not feasible for certain States to meet environmental targets imposed by the SES performance scheme.

Acceptance assessment

When assessing the challenges associated with implementing operational improvements, it is important to consider not only the consequences for airlines and air navigation service providers, but also the impact on passengers. Their decision to buy a ticket has a strong impact on the entire aviation system.

Longer flight times result in longer trips for passengers and longer boarding times. Higher fuel consumption could lead to higher ticket prices. On the one hand, both aspects reduce the attractiveness for passengers, which may lead to a decrease in ticket sales and thus in airline revenues. Especially on shorter continental routes, passengers might prefer existing transportation alternatives (e.g., train travel) to flying. On the other hand, it was observed in the ClimOP survey that passengers' ecological awareness influences their decision and they are willing to accept higher efforts if these are associated with a climate benefit.

C. Uncertainty estimate

When interpreting the climate impact of this OI as well as comparing it with others, the main uncertainties are:

- **Uncertainties for engine emissions**: In emissions modelling (fuel flow correlation method), uncertainties arise from flight performance assumptions based on BADA4 as well as weight uncertainties currently assumed with an average European load factor. Different atmospheric parameters may also have an impact on the results. Overall, these uncertainties are expected to have little impact on fuel flow, flight time, and emission levels. The accuracy of engine emissions is estimated to be about ± 25% for CO_2 and ± 50% for NO_x.
- **Uncertainties from climate modelling:** The basic climate modelling calculation (combined uncertainty) from chemistry climate models and the radiative transfer scheme in this simulation build a major uncertainty. Sources for uncertainties are the process representation in global chemistry models (the chemistry scheme, the cloud parameterization or the horizontal and vertical resolution), the calculation of GHG concentration changes, temperature calculations (Temperature change calculation depends on assumptions on efficacy and temporal evolution of emissions/RF) and physical climate metric (ATR, climate metric has to be appropriate for the targeted climate objective, but still allows some variations with respect to assumptions on background emission scenario/model, emissions evolution (pulse/sustained/future scenario), climate indication, such as averaged temperature response, and time horizon). Furthermore, the aCCFs calculated from such climate model data are affected by these uncertainties as CCF data depends on the meteorology at the location of the emission. The quality of the meteorological forecast used for the ATR20 calculation is subject to uncertainties, since the weather forecast data contains deviations from the real conditions, which are measured by the quality of the forecast and its capabilities. Especially contrail effects underlie considerable uncertainties. That is why a more detailed analysis has been performed applying different scaling factors.

D. Comparability of the results with the other OIs

The modelling approaches and climate metrics, as well as the temporal and geographic scale, make all trajectory-related OIs comparable. Results for these OIs were obtained for a representative day that was also used in LOSL and FREE/WIND. While the magnitude of results as well as the relative mitigation potential can be compared to other IOs, the absolute numbers must be treated with caution due to the wide range of assumptions made in the modelling process. Since CLIM uses a BAU scenario (future emission scenario-based F-ATR), while LOSL and FREE/Wind use a pulse scenario, the ATR20 values in the CLIM OI are about ten times higher because the impacts of operating this alternative strategy over the next 20 years are examined.

The results of this OI can be extrapolated to a full European scenario including all routes to, from and within the ECAC area and the full share of ASK in 2018. However, extrapolation must be done with caution as the results were only calculated in detail for the selected scope and assumptions. Various limitations made in the course of modelling must be considered in this context:

- Temporal Scope: The results were calculated for a selected day and night flights. However, the methodology of selecting this representative day allows extrapolation to the entire year 2018.
- Selection of aircraft types: We have limited our analysis to four specific aircraft types that cover a large portion of all ECAC ASK. Assuming an equivalent correlation for the other aircraft types, we assume a proportional relationship between ATR20 and ASK if the sample size is large enough and covers a wide variety of routes and aircraft types.
- Geographical scope: For one selected day, no geographic restrictions have been performed, so that these results are representative for all flights from and to as well as within the ECAC area.

E. Applicability of the OI

This OI will require development of corresponding SESAR solutions, which need to be implemented via the European ATM Master Plan. Conceptually speaking, this OI does not require the implementation of expensive equipment, neither onboard nor on the ground segment. However, new flight dispatching working methods and procedures and possibly system upgrades would have to be implemented in the airlines OCCs to consider the potential constraints that represent not to fly in/out to avoid the sensitive areas, which would be an increase of OPEX for the airspace users, as systems would have to be modified/upgraded accordingly. Additionally, a close and functional link to weather service is a prerequisite for the reliable weather forecast required as an input to aCCFs.

Climate-optimization procedures which reduce the total climate effects can go hand-in-hand with an increase in cash operating costs (COC), but airlines have little incentive to voluntarily bear these additional costs, if there are no regulations applying to the total climate effect. The crucial question, then, is how to create a monetary incentive for airlines to minimize flight times and emissions in particularly climate-sensitive regions. One environmental policy option is to impose a climate levy or a climate restriction on operators of aircraft flying in these areas. In these approaches, an airspace area is charged with an environmental unit fee per kilometre flown if its specific climate impact in terms of aircraft emissions exceeds a certain threshold. In order to cut climate charges and hence resulting COC, cost-minimizing airlines will choose to fly longer and re-route their flights away from more expensive airspace areas. In this way, the cutting of costs coincides with climate impact mitigation. Alternatively, the operator of an aircraft can also minimise flight time and pay compensation for higher climate damage. The regulatory feasibility will be investigated in D3.1.

Conclusions

The simulation of the CLIM OI shows that mitigation potentials and associated mitigation gains in terms of climate effect show a strong variation with the individual city pair but also the meteorological situation or geographic region of the flight. Further comprehensive studies are needed to provide a more detailed quantitative estimate of mitigation gains, but also associated influence on other performance indicators.

A.4 Strategic planning: merge/separate flights, optimal network operations

Strategic network planning is based on many decisions according to allocating the fleet to routes that eventually form the entire operating network of an airline. The main objectives followed in the involved decisions are the monetary aspect of allocating each fleet type to a route and its network implication in terms of connecting passengers fed to other flights at the hub by opening that route. On the other hand, considering the climate impacts of the flights while planning an airline's network is believed to be a helpful step in mitigating the aviation climate footprint at the airline level.

This study aims to model airline planning decisions using a multi-agent system and measure the consequences of limiting an airline's total yearly climate impact on the profit, ATR20, and other KPIs listed in the previous deliverables. To tackle this problem, we assumed that flights in the ECAC area (including international flights with an origin or destination in this area) are operated by three main types of airlines, namely, main hub-and-spoke, secondary hub-and-spoke, and low-cost carriers. One representative airline for each mentioned type has been chosen, and the multi-agent model will be used to calculate the desired KPIs. In order to find the impact of this OI at the ECAC level, results from each representative airline will be scaled up based on the fleet number for all airlines with similar types and operating areas. In this deliverable, the results for the KLM airline (the representative airline of the main hub-and-spoke type) are represented. While the network planning has been studied for years, incorporating the climate impact as well the profit is a novel approach, which is followed in this study.

Methodology

The study is divided into three consecutive steps with the final goal of estimating the potential mitigation of climate impact at the airline network planning level. Figure 16 illustrates the following.

1. <u>Climate impact and emission generation</u>

The passenger itinerary and flight schedule data for each representative airline are extracted based on the study's desired geographical and year assumptions. By having the list of airports that representative airlines served, the climate impact in terms of ATR20 and ATR100, as well as the emissions and fuel flow for all aircraft in the airline fleet, were computed following the same workflow in the ISOC OI. For ODs with a distance of more than 2500 NM, the associated data for intermediate stop operation is also calculated to be used in the integrated scenario.

Although the list of the routes operated by each airline indicates limited types of aircraft (in most cases, only one) are being used in each route at a time, the climate and non-climate input data are calculated for all aircraft types in the airline’s fleet which can be used in all routes. This approach would make a broad mix and match pool to operate a route with the possible aircraft. This approach has a significant impact on improving profit or climate impact objectives. Having the same workflow to generate the input data in network-related OIs would provide an acceptable level of result inter-comparability of the final results.

2. Airline strategic network planning

AOMAS model is utilised to find a better trade-off between climate and profit in network planning. The preprocessed data from the previous step allows AOMAS to generate an estimated Pareto frontier and propose a schedule that is expected to have less climate impact in terms ATR20 for all airline types. The network optimization is carried out for each airline type given the demand, ATR, costs, and airfare per route separately in each quarter of 2018. Aggregated results of all quarters will indicate the OI effect in 2018. The network planning is aimed to have the minimum deviation in the list of the ODs severed by the airline, which facilitates the practical implementation of the OI. The results in this step are generated while considering the differences in the business models and operation conditions of the representative airlines.

3. Extrapolation of the result to cover the same airline types in Europe

The result in the previous stage is an estimation of the effect of implementing this OI for the studied representative airlines. To extrapolate the result to the European level, a comprehensive list of similar airline types which are operating in the ECAC area is compiled. The fleet size is the main criterion which was used to scale up the result from the airline level to the full scale.

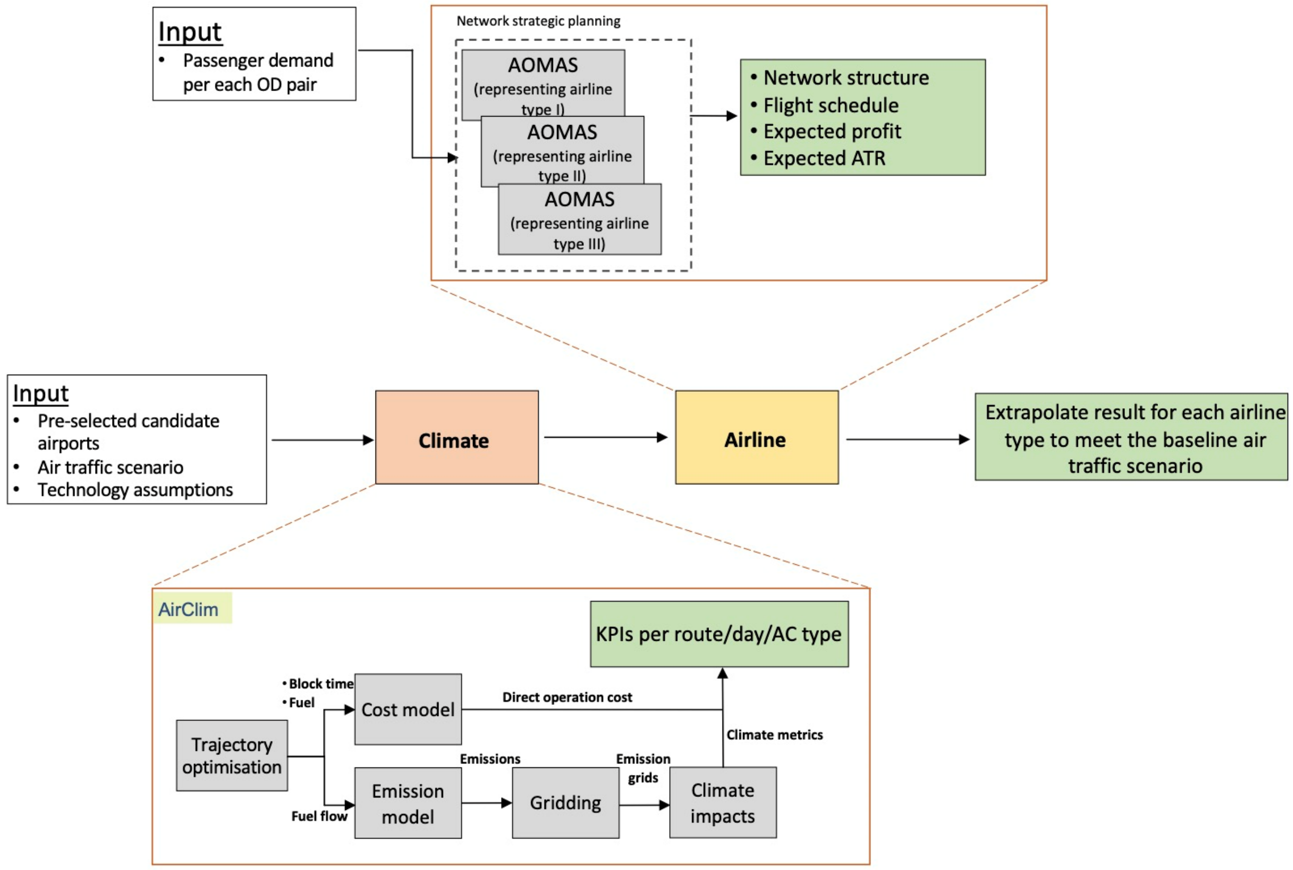


Figure 20. Model workflow for OI of NETW

A broad list of KPIs is considered to measure the implications of implementing NETW for climate and non-climate aspects. We also included other KPIs driven indirectly from the main KPIs list and delivered a more in-depth insight into the changes than the business-as-usual case. Table 26 summarises all primary and secondary KPIs computed in this study. The threshold of categorising the flights into short and long haul is 4500 kilometres(km), which means flights with more than 4500 distance are in the long-haul category and the rest of the flights are in the short-haul category.

Table 26. Climate and non-climate KPIs

Climate KPIs		Non-climate KPIs	
Total ATR20	Total ATR100	# OD served	# total number of AC used
ATR20 (Long-haul)	ATR20 (Short-haul)	# short/medium haul flights	# long haul flights
ATR100 (Long-haul)	ATR100 (Short-haul)	Pax served	Pax connected
Total CO_2	Total H_2O	Seats offered	Average load-factor
Total NO_x	Total HC	ASK	RSK
Total SO_2	Total CO	Average fleet utilization	Total # ISO
Total Soot		Net earnings(Profit)	

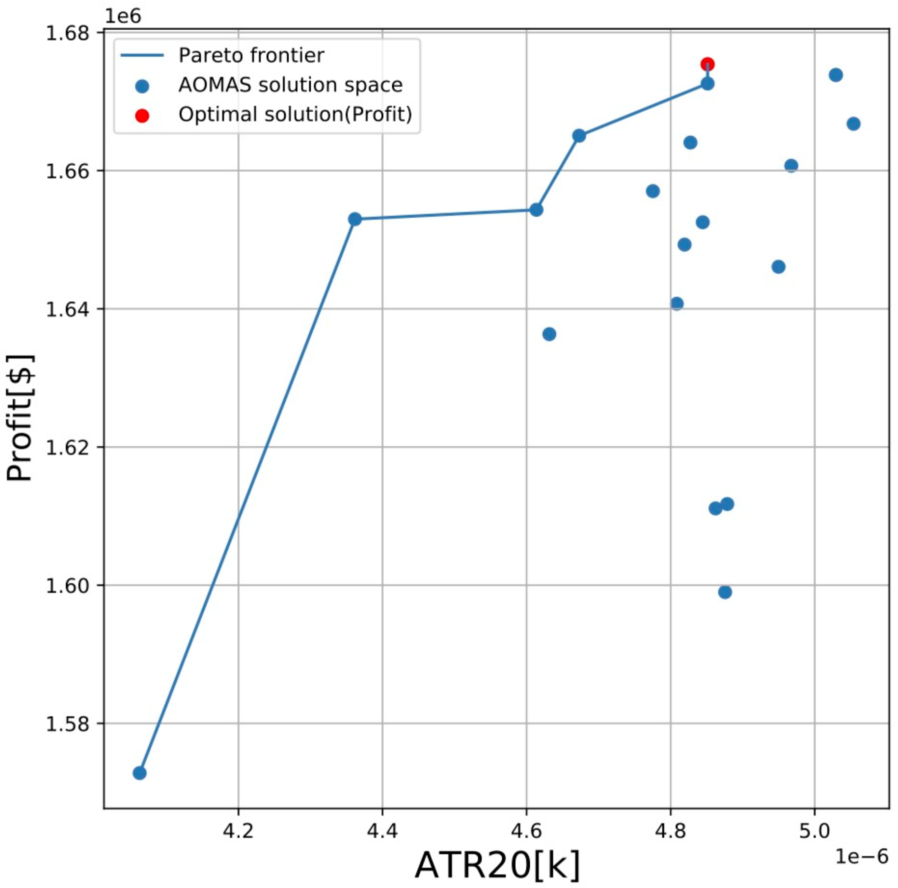


Figure 21. AOMAS solution selection based on the Pareto frontier

AOMAS has a multi-agent optimization approach that can adopt single objective (Profit) and bi-objective optimization. Bi-objective optimization is executed based on the total ATR20 and the Profit iteratively [11]. Bi-objective optimization needs to prioritise the objectives while selecting the solution from the non-dominated solution set. The objective weights are used in bi-objective optimization to select a solution from the solution set.

Within the AOMAS, the trade-off value is 0.9, which means a maximum of 10 percent violation from the optimal solution is allowed in each iteration. Figure 21 presents the Pareto frontier in an iteration of AOMAS. The red dot is the optimal solution in that iteration (only based on Profit), considering ATR20 would allow us to choose another solution on the frontier according to the allowed trade-off value. Each point in the following figure represents an aircraft assigned to a set of routes. The entire network scheme is cumulatively added to all these partial solutions.

Results

The results and the comparison before and after implementing NEWT for all the representative airlines are presented in this section. The AOMAS model was executed for two rounds for each airline. Firstly, only the profit objective is considered for network optimization, and the resulting solution is assumed to be the airline operational plan in the business-as-usual state. Secondly, the ATR20 objective is also involved in optimising the bi-objective model. The result of the second round will indicate the expected adaptation of the airline network to the limitations imposed by the climate impact objective. In both rounds of optimization, all the input data for the underlying airline will remain the same. The fleet size and composition for the representative airlines are set based on their available fleet in 2018. A more detailed representation of the changes in the climate KPIs for the first quarter of 2018 is provided for each airline type. Finally, an aggregated result for the expected potential of this OI is also delivered in table 23.

Assessment of KPIs

<u>AirClim results analysis</u>

To make a more detailed interpretation of the result in this OI, AirClim data had been investigated in the first place. The main goal of this section is to find the values of the ATR20 for different routes in the representative airline network. As AOMAS uses Profit and ATR20 to replan the network, presenting the ATR20 trend according to the distance of the flight would help distinguish and evaluate the results of AOMAS. A linear regression model was used to represent the change in the ATR20 value vs. distance of the flight for three aircraft types for each airline. Figure 22 presents the result of the regression model.

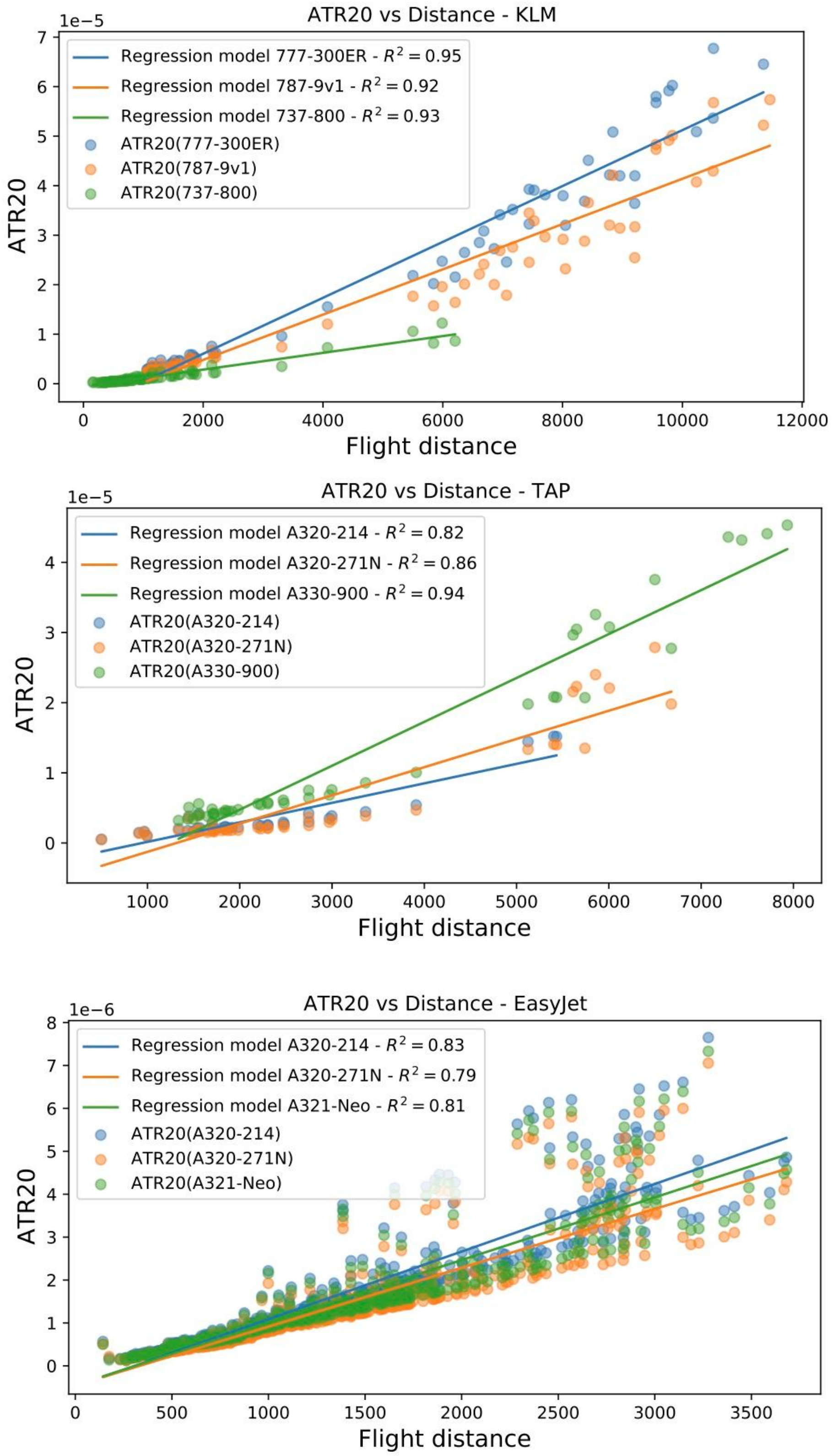


Figure 22. ATR20 vs. flight distance regression model for representative airlines

Results indicate that over 92% of the change in the ATR20 for wide-body aircraft and medium to long haul routes is related to the distance of the flight rather than the OD. This number for narrow bodies and short-haul routes is about 85 percent. Such a high R-square would be interpreted as a highly influential driver in the values for the routing decisions in the AOMAS. In other words, aiming to decrease the ATR would be more beneficial if changes were steered to the long-haul flight because long-haul flights contribute much more to the total ATR20 of an airline than the short-haul ones.

On the other hand, short-haul flights have a more random distribution of changes of ATR20 vs. flight distance. In case of a short flight, passenger demand, airfare, and ATR20 of the route will be evaluated in the AOMAS to find the replanned network. The analysis in this section can explain the changes in the frequency of long-haul flights in the replanned network. As long-haul flights naturally have more ATR20, they have the most effect on the climate impact objection when they get changed.

<u>KLM case study</u>

The KLM airline business model depends on connecting passengers to make all the flights in an itinerary profitable. On the other hand, the profit margin is relatively low compared to the other two airline types. As a result, the fleet is used to its maximum possible utilisation rate. When the climate impact objective comes into play, the model starts to cut down the frequencies of the flights with the maximum ATR20 and minimum profit. In most cases, such flights are selected from long-haul flights. Although long-haul routes are usually more profitable than short-haul, their ATR20 values are also higher than a short-haul 200 to 500 percent based on the route and the aircraft types which are used. Comparing the reduction of the total ATR20 and the ATR20 (LH) suggests over 82% of the total ATR20 reduction is due to the reduction in long-haul flights.

To keep the profit within the allowed threshold, reductions in the long-haul flights are compensated by increasing the number of flights in the short and medium range. Other non-climate KPIs indicate implications of implementing such a strategy. For instance, Pax served, load-factor, or RSK, is increased compared to business as usual, but the final profit could not be able to recover to its initial level. As a result, the KLM network seems to have enough opportunities to keep the profit reduction due to flying greener relatively small. The main reason would be a diverse range of destination and fleet types that can adapt to the new operation strategy more efficiently.

<u>TAP case study</u>

The connecting passengers in the TAP airline are also quite important (as the network structure is also H&S), but not in the way it was in the KLM case. In contrast to the KLM, some relatively independent routes could still be modified in favour of the ATR20 objective without a significant network effect on the other routes. Considering this fact, a relatively more remarkable improvement in the ATR20 could be achieved by modifying the long-haul flights, which slightly affects the profit. On the other hand, TAP has many destinations in the common interval for short to medium and long-haul range. Having such a diversity in the destination ranges carries the capability of accommodating the wide-body aircraft which are not flying to their long-haul destination into some medium-range destinations. As a result, we see an increase in ATR20 associated with short-haul flights along with a decrease in long-haul ATR20. Because long-haul flights have significantly more ATR20, the total ATR20 was decreased by nearly 8.3%.

As presented in Figure 23, most of the emission species are reduced compared to the reference operation scenario. It is in agreement with the fact that in the bi-objective optimised solution the free utilisation capacity became available to the wide bodies is assigned to the flights which are still profitable to be operated by wide bodies but not categorised in the long-haul category.

The network operated by TAP does not show the flexibility to adapt to the new operational strategy, and the profitability would drop to a much lower level for a climate-optimised network. The fleet composition of TAP is designed to operate short to medium haul flights, and a small number of aircraft are available to serve the long-haul destinations. This fact would lead to significant reductions when changing the long-haul route schedule. The same compensation behaviour is also visible in this case study, which boosts the short-haul flights to recover the total profit of the airline.

EasyJet case study

EasyJet is operating a point-to-point network containing only short-haul flights. As short-haul flights have minor ATR20 values compared to the long-haul flights, we cannot expect a major reduction in the absolute climate impact reduction in this case study. The other reason why the climate impact mitigation is relatively low in this case is that the climate impact value for different routes in the easyJet network is relatively close when normalised by the distance. This will lead to the situation in which there is no significantly preferable route with a significantly different ATR20 value than the competing routes. In conclusion, EasyJet's relative climate impact mitigation will be limited to 2.9%.

A further improvement in the ATR20 is also possible by further reduction of the profit which will necessarily result in less fleet utilisation. The associated network structure with the smaller ATR20 values can be obtained from the solution evolution diagram given in the economical assessment section.

EasyJet network is also susceptible to the new strategy of fleet operation suggested in this study. Almost all of the routes are in the same range of distance. On top of that, a homogenous fleet of narrow-body aircraft would not offer the flexibility to reduce the ATR20 with a slight profit reduction. So we would have either a significant ATR20 reduction with a relatively high decrease in the profit or a slight change for both of these variables.

Analysing the non-climate KPIs in this case, all quarters show a reduction in all KPIs. As point-to-point network operations are independently operated regardless of other routes, the main objective in the business-as-usual state would be using the aircraft as much as possible based on the recognized demand of the routes. Such a goal will result in near maximum utilization of the available fleet. Any change in this schedule would have lower non-climate KPIs as it will not be able to meet the reachable utilization values regardless of the ATR20 considerations.

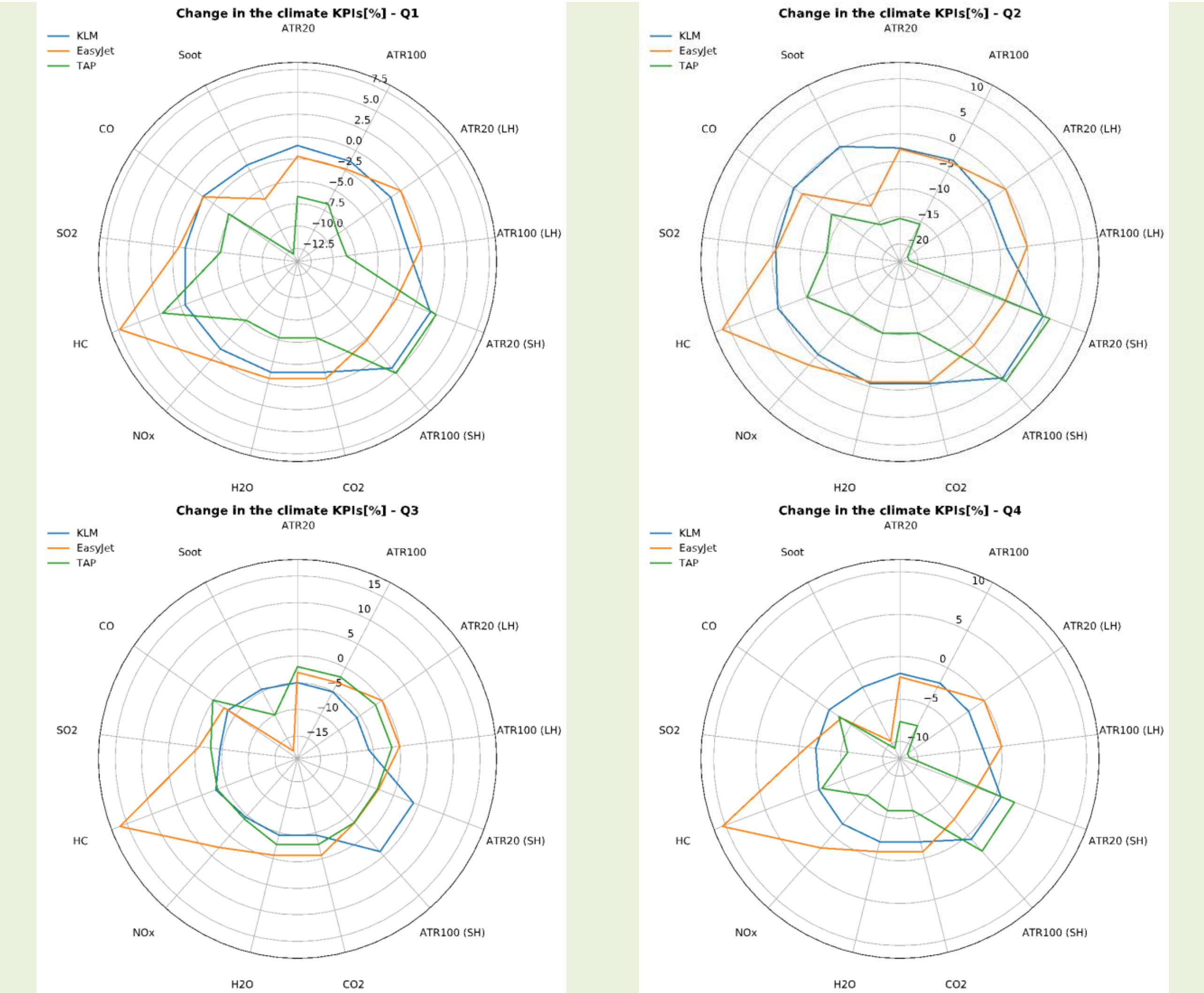


Figure 23. Climate KPIs relative change in compared to the business-as-usual

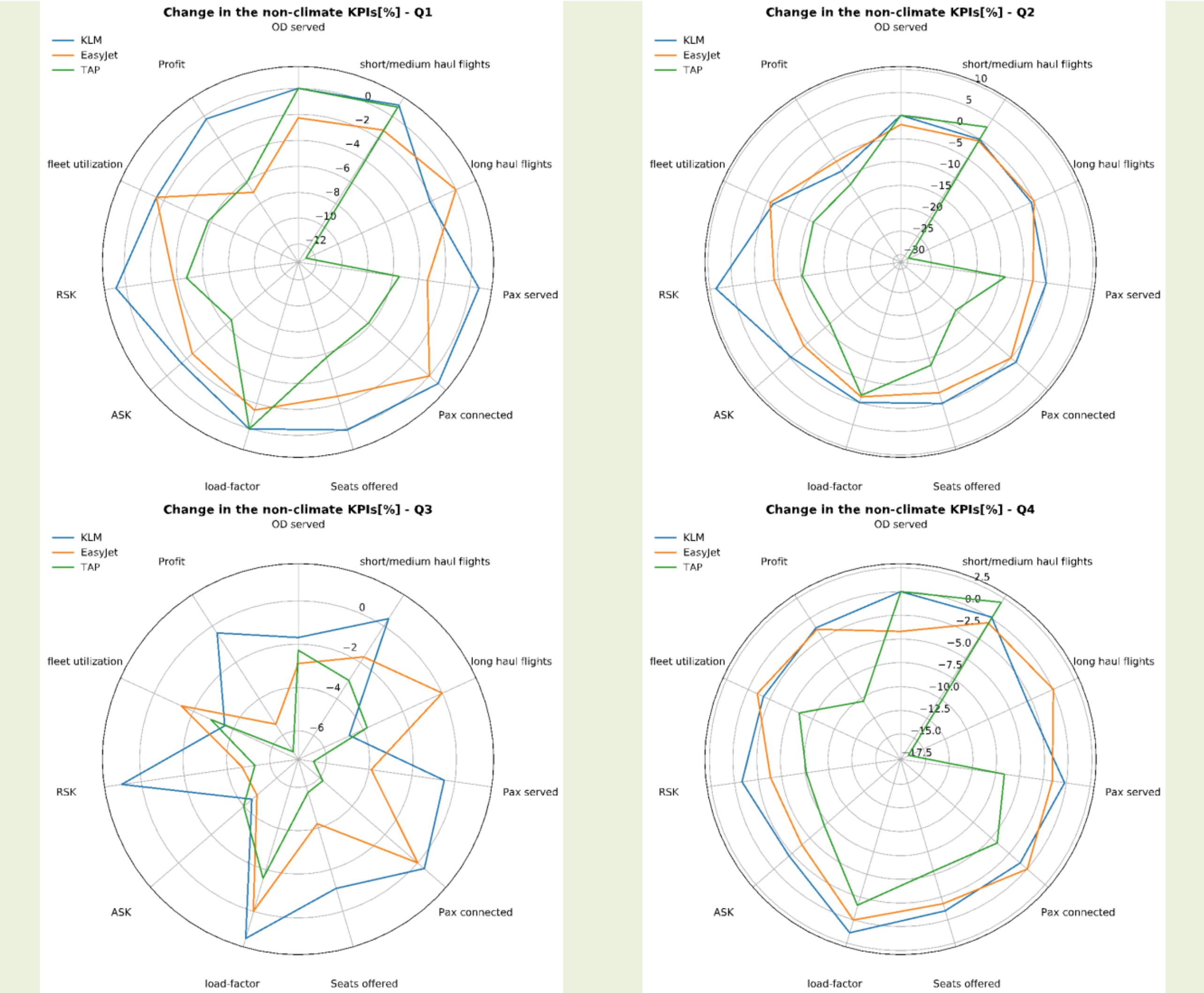


Figure 24. Non-climate KPIs relative change in compared to the business-as-usual

Aggregated results

A weighted average approach used to extrapolate the results for each airline type in each quarter of 2018 for all the airlines within the same category. List of the airlines and their fleet size is presented in the airline list section. The results are then aggregated for all airline types and quarters to find the absolute total expected change in the climate impact. In table 27 the aggregate results for each airline type and each quarter are presented.

Table 27. Aggregated climate impact (ATR20) improvement [mK] after implementing NETW

	Q1	Q2	Q3	Q4	Total
Main H&S	3.90E-02	9.92E-02	2.03E-01	8.33E-02	4.24E-01
LCC	1.77E-02	2.30E-02	2.68E-02	2.15E-02	8.89E-02
Secondary H&S	1.82E-01	3.85E-01	5.08E-02	1.86E-01	8.04E-01
Total	2.39E-01	5.07E-01	2.80E-01	2.91E-01	**1.32E+00**

Table 28. Aggregated climate impact (ATR20) changes[%] after implementing NETW

	Q1	Q2	Q3	Q4	Total
Main H&S	-2.13	-5.55	-10.67	-4.27	-5.69
LCC	-0.88	-1.12	-1.24	-0.95	-1.05
Secondary H&S	-10.88	-25.00	-3.25	-12.50	-12.91

Table 29. Aggregated climate impact (ATR100) improvement [mK] after implementing NETW

	Q1	Q2	Q3	Q4	Total
Main H&S	3.25E-02	6.12E-02	1.33E-01	5.36E-02	2.80E-01
LCC	1.17E-01	1.56E-02	1.74E-02	1.42E-02	1.64E-01
Secondary H&S	1.18E-01	2.52E-01	3.30E-02	1.21E-01	5.25E-01
Total	2.68E-01	3.29E-01	1.83E-01	1.89E-01	**9.69E-01**

Table 30. Aggregated climate impact (ATR100) changes [%] after implementing NETW

	Q1	Q2	Q3	Q4	Total
Main H&S	-2.77	-5.33	-10.88	-4.27	-5.81
LCC	-0.92	-1.20	-1.28	-0.99	-1.10
Secondary H&S	-10.88	-25.16	-3.25	-12.50	-12.95

<u>Economic assessment</u>

To facilitate the economic assessment of the NETW we have estimated the solution evolution profile to measure the trade-off between the two main objectives which are considered in this study. AOMAS generates the plan for the new network in an iteration fashion to avoid local minimum and incorporates the operational interdependencies in the solution. The values of the ATR20 and profit are depicted in the following figures to show how solution development takes place within the AOMAS. Small jumps in the course of optimization are due to the multi-agent negotiation process, which ensures it passes a local minimum.

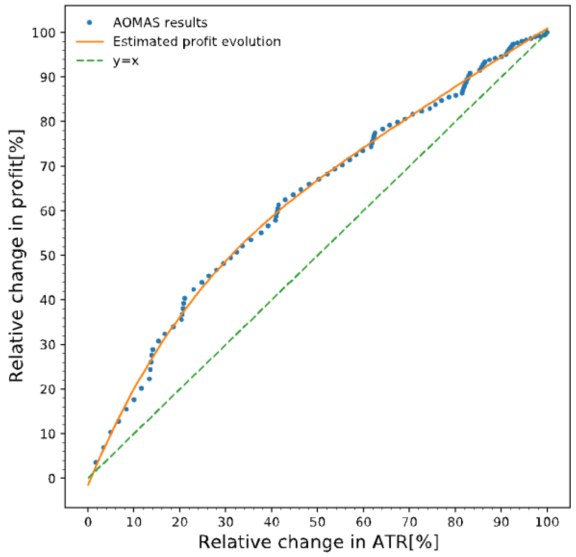


Figure 25. KLM solution evolution profile

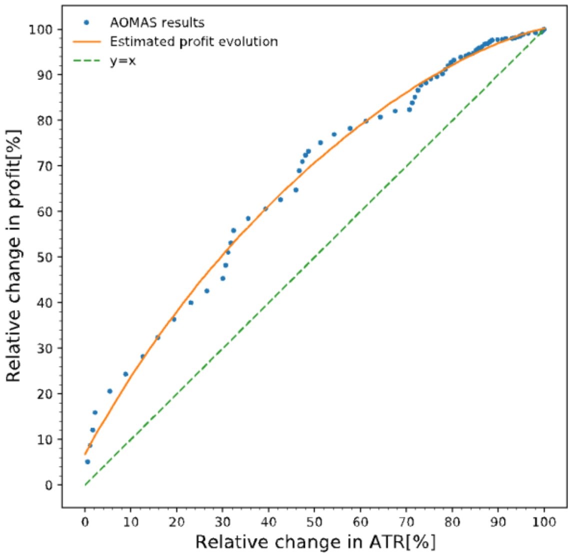


Figure 26. TAP solution evolution profile

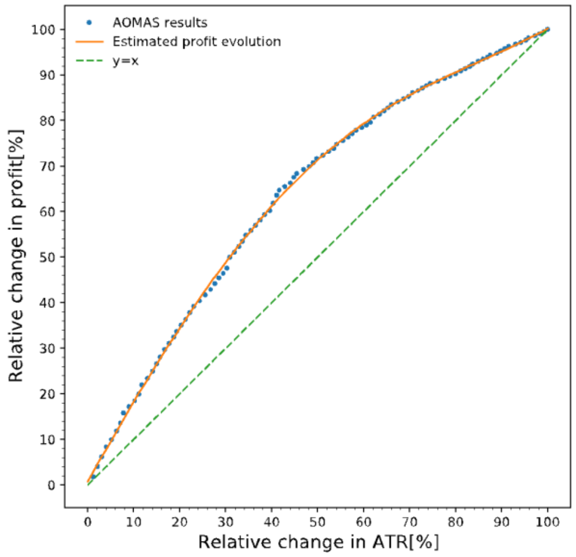


Figure 27. EasyJet solution evolution profile

Human performance assessment

The following table collects the changes on Human Performance Arguments areas (Roles and Responsibilities, Human and Systems, Teams & Communication, HP Related Transition Factors) introduced by NETW. The identification of relevant arguments is the first step for HP assessment.

Table 31. Description of change in human performance

HP Argument branch	Change & Affected Actors
1. Roles & Responsibilities	
1.1. Roles & Responsibilities	Airlines planners and schedulers, passengers. Airline planners and schedulers will have to consider ATR20 in their optimizations to plan the network according to the impact on climate and operational aspects [9]. On the other hand, passengers may face longer travelling time and additional costs on some routes or several connecting flights rather than a single long-haul.
1.2 Operating methods	Operating methods in normal and abnormal conditions will not change. SNP will be required to plan the routes according to the optimal trade-off between fuel efficiency and climate impact [10].
1.3 Tasks	Airlines are continuously checking and doing route studies for the commercial department. Studies already include seasonal weather considerations, fuel burn based on Time-Cost-Fuel, and other operational aspects [17]. The NETW concept will require SNP to consider additional information for optimal network planning [11].
2. Human & System	
2.1. Allocation of tasks (Human & System)	A decision-making tool might be required to support SNP making decisions based on their impact on ATR20.
2.2. Performance of Technical System	This is still to be defined.
2.3. Human-Machine Interface	No Graphical User Interface is predicted, the information will be provided by an excel file as input and output. This is expected to increase the efficiency of the decision process. Several smart error detection mechanisms are also in place to avoid unwanted errors in the input data.
3. **Team & Communication**	
3.1. Team Composition	No change is expected for team composition if the planners/schedulers are instructed on how to use the envisioned tool. No new role is necessary [10].
3.2. Allocation of tasks	As there are no changes in the roles and task allocation, no change in the human performance is expected [9].
3.3. Communication	No changes in communication are foreseen.
4. HP related transition factors	
4.1. Acceptance & Job satisfaction	Airlines may prefer to avoid including an additional constraint in SNP [17]. As passengers may face longer travelling time and additional costs on some routes, this might prevent them from accepting the NETW concept.

4.2. Competence requirements	In some cases, a training course would facilitate the transition phase of getting used to the new technical tool.
4.3. Staffing requirements & staffing levels	No changes to staffing requirements and staffing levels are foreseen.
4.4 Requirement and Selection	No changes in staff requirement and selection are foreseen.
4.5 Training Needs	Training course will facilitate the transition phase of getting used to the new technical tool.

Table 31 lead to two high-level hypotheses that guided the high-level validation of the change associated with the NETW concept:

- Airlines may require a decision-supporting tool for an optimal SNP that considers the network impact on ATR20.
- Passengers may be reluctant to spend more time or money to travel to the same destination, even knowing that this would be beneficial for reducing climate change.

The ClimOP project assessed the impact associated with the NETW concept on human actors through qualitative data collection and desk review. The effect of NETW on passengers was assessed by the Survey on Social Acceptance, thanks to a set of items on intermediate stop-over operations, baggage limitation, less frequent flight connections and travelling with larger-fully-booked aircraft.

The results on the questions related to ISO show a neutral stance on 2 to 3-segment instead of direct flights and a slight preference for longer stops to explore the city. Results of NETW-related items show passengers to prefer less frequent flight connections and larger, fully-booked aircraft than baggage limitations (cf. Appendix C for the detailed analysis of the results).

On the other hand, the airline's perspective was grasped thanks to the desk analysis made on the IATA's review of operational improvements. Airlines appeared to be affected by the economic disadvantages associated with the NETW concept rather than the impact on human performance [17].

It might be necessary to introduce a tool to support SNP decision-making considering the impact on ATR20. It is suggested to assess the impact on HP obtained using the tool to support the decision process suggested in the NETW concept at a later stage.

Uncertainty estimate

The main uncertainty sources in this OI relate to the input climate data which was generated with the same method used in the ISOC OI. So, the same uncertainties related to the ISO also hold in this OI as well. Other than that, we assumed a static and deterministic demand which is not the case in most cases. Passenger demand would change by changing the schedule and frequency of flights. To investigate the changes, research regarding discrete choice analysis would be necessary. Literature on this topic study has been done to have a qualitative overview of the possible changes. The results suggest that demand per route for airlines is following an S-shaped curve representing the airline market share of the route. The curse increases by the frequency of the flight on each route. On the other hand, the frequency of the flights is proportional to the number of opportunities to make a connection at the hub airport for hub-and-spoke airlines.

The changes in the frequency and the connection at the hub would have a very high impact on the passenger demand. To avoid such drastic changes, we limited the allowed changes in the profit objective. This limitation will lead to the minimum deviation from the optimum profit solution, which means the connections and routes will be changed as minimum as possible.

NETW has investigated the exact implications of incorporating climate impact objective in the network planning, and the results were extrapolated for the rest of similar airlines operating in the ECAC area. The extrapolation was executed assuming that all airlines in the same category would adjust their network with the same strategy as representative airlines did. The fleet size was used to extrapolate the result, which may not represent the real difference among the airlines which are being studied. Quantifying the underlying uncertainty may not be possible as the airlines of the same types could follow very different business models. Still, it is essential to mention that extending the result from an airline to all similar airlines will need elaborate modelling and assumption, but we have assumed that fleet size would be an adequate parameter to calculate the difference in the other airlines.

Comparability of the results with the other OIs

The study in this OI considered three airline types and measured the changes in the KPIs for each type based on the tailored optimization setup. To improve the accuracy of the results, the same model was solved based on the associated quarterly data for the year 2018. Then the yearly result of the representative airlines was extrapolated for all the airlines with the same type operating in Europe.

Besides that, additional restrictions were taken into account while running the model, which should be considered in the harmonisation and comparability:

- Maintenance and crew limitations and availability were not considered in the modelling of this OI. All the flights are assumed to be on time, and crews are always available for the flight
- Cost and revenue have been modelled using the average figures in 2018 for each route. A revenue management strategy could have an effect on the reported profitability of the flights
- airport slots are assumed to be flexible and available in case changes in the schedule is needed

Applicability of the OI

No specific restriction of preparation is needed to implement this OI. The only consideration in the implementation phase would be regarding the changes in the airport slots. The changes in the slots of congested airports would need extra negotiation and may follow additional costs. Other than that, some specific considerations which are based on a specific airline may need to be considered in the implementation. Specific maintenance policies and strategies related to keeping operation a route, although it’s not profitable, are some specific adjustments that could be easily implemented in the model but needs accurate data about expectation and facts in that regard.

Conclusions

In conclusion, AOMAS brings a unique opportunity to quantify the trade-off between the profit and climate impact at the airline level. Our results for three studies on airline types suggest that the profit vs. climate impact reduction rate is highly dependent on the airline type. In airlines with an H&S network structure, the profit is much more sensitive to the changes in the climate impact of the network. As the change in the flights will change the inflow of connecting demand and outbound flights from the hub airport in most cases are profitable only in case they receive their connecting passengers from inbound flights. The results from our detailed study of strategic network planning considering climate impact provide a promising opportunity for airlines to include the climate impact and profit when designing their network.

The main goal of this OI was to investigate the flexibility of the airline operations to adapt to a greener network while keeping their operational infrastructure and procurements with the minimum change. It was shown that main hub-and-spoke airlines are much more flexible in their network as they operate in a wide range of destinations and have a diverse fleet configuration. Given these facts, they can recover most of their profitability even after changing their network to one which is optimised for climate impact and profit rather than the one optimised only for profit.

Airline list

Here is the list of European airlines used to extrapolate the result. The airline lists are filtered and categorised based on their fleet size and network structure. Airlines with heterogeneous fleet compositions and the size of more than 100 aircraft which operate in a hub-and-spoke network are considered as main hub-and-spoke airlines. Other hub-and-spoke airlines with a heterogeneous fleet that has intercontinental flights are considered secondary hubs and spoke. Finally, the low-cost carriers with more than ten aircraft fleets are also listed under LCC.

Table 32. Main hub-and-spoke airlines

Rows	Name	IATA	ICAO	Fleet size
1	KLM	KL	KLM	105
2	Scandinavian Airlines	SK	SAS	123
3	Air France	AF	AFR	211
4	Lufthansa	LH	DLH	277
5	Turkish Airlines	THY	TK	373
6	British Airways	BA	BAW/SHT	254

Table 33. Secondary hub-and-spoke airlines

Rows	Name	IATA	ICAO	Fleet size
1	TAP Air Portugal	TAP	TP	81
2	Air Belgium	KF	ABB	8
3	Bulgaria Air	FB	LZB	12
4	Croatia Airlines	OU	CTN	13
5	Transavia France			61
6	Lufthansa CityLine	CL	CLH	49
7	TUI fly Deutschland	X3	HLX	27
8	Olympic Air	OAL	OA	17
9	Sky Express	SEH	GQ	21
10	CityJet	WX	BCY	20
11	Neos	NO	NOS	15
12	Luxair	LG[2]	LGL	19
13	Air Malta	KM	AMC	7
14	KLM Cityhopper	WA	KLC	58
15	Transavia	HV	TRA	42
16	TUI Airlines Netherlands	OR	TFL	12
17	TAROM	RO	ROT	22
18	Air Europa	UX	AEA	36
19	Volotea	V7	VOE	36
20	Belavia	B2	BRU	14
21	Anadolujet	AJA	TK	53
22	Corendon Airlines	CAI	XC	23
23	Pegasus Airlines	PGT	PC	88
24	SunExpress	SXS	XQ	53
25	Virgin Atlantic	VS	VIR	36

26	Austrian Airlines	OS	AUA	61
27	Brussels Airlines	SN	BEL	39
28	TUIfly Belgium	TB	JAF	30
29	Finnair	AY	FIN	80
30	Aegean Airlines	AEE	A3	53
31	Aer Lingus	EI	EIN	51
32	ITA Airways	AZ	ITY	58
33	Air Baltic	BT	BTI	34
34	LOT Polish Airlines	LO[1]	LOT	75
35	Iberia	IB	IBE	76
36	Azerbaijan Airlines	J2	AHY	23
37	Icelandair	FI	ICE	38
38	Air Serbia	ASL	JU	18
39	Swiss International Air Lines	LX	SWR	90

Table 34. Low-cost-carries airlines

Rows	Name	IATA	ICAO	Fleet size
1	easyJet Europe	EC	EJU	142
2	Eurowings			113
3	Smartwings	QS	TVS	34
4	Wizz Air	W6	WZZ	142
5	Ryanair	FR	RYR	504
6	Malta Air	AL	MAY	144
7	Iberia Express	I2	IBS	21
8	Vueling	VY	VLG	126
9	Norwegian Air Sweden	DY	NAX	29
10	Norwegian Air Shuttle	DY	NAX	165
11	SkyUp	SQP	PQ	15

12	Scandinavian Airlines Ireland		SZS	10
13	Blue Air	0B	BLA	15

A.5 Climate-optimised intermediate stop-over

Fuel efficiency of long-haul missions can be increased by reducing the stage length, because less fuel has to be carried and resulting weight reduction leads to less required fuel on the respective mission. This is addressed by the concept of intermediate stop operations (ISO). Instead of performing a direct long-haul flight, the mission is interrupted by an intermediate landing for refuelling. Less fuel has to be carried, weight and thus fuel consumption can be reduced. Previous studies [21][22][23] have shown a fuel-saving potential of approximately 5% on a global scale of long-range flights, which is associated with a proportional effect on CO_2 emissions and their climate impact. By contrast, climate impact from non-CO_2 emissions such as NO_x, H_2O and contrail formation increases in general [22]. This can be explained by the fact that the climate impact of these emissions varies in dependence of their altitude, location and atmospheric boundary conditions. In the course of fuel optimisation on ISO missions, emissions are released at higher altitudes as cruise levels are shifted to higher more climate sensitive areas because of the aircraft's reduced weight. Furthermore, the location of the ISO airport is not selected based on climate-optimising criteria but based on minimum detour and eccentricity resulting from an intermediate stop at this location.

While the ISO concept has been analysed comprehensively for fuel-optimal solutions, this OI investigates the innovative aspect of climate-optimised ISO. Thus, the goal is to minimise the climate impact from both CO_2 and non-CO_2 emissions by selecting the intermediate stop airport on climate-related criteria. To achieve additional savings, a limitation of flight altitudes is applied to avoid emissions in highly climate-sensitive areas. A comparison of the reference case (non-stop missions) and the fuel-optimal ISO case with the climate-optimised scenarios for relevant KPIs of fuel burn, trip time and average temperature response (ATR) does not only prove climate mitigation potentials, but also affects the Stakeholders of the air transportation system.

Methodology

The modelling workflow and the utilised database have already been described in Deliverables D2.1, D2.2 and D2.3 [9][10][11]. A summary of the workflow is shown in Figure 28. Basis of the applied methodology is the comparison of the non-stop reference case, which aims to model the status quo as good as possible, with different implementation scenarios of the ISO concept. A comparison can be performed based on ATR20 and ATR100 as well as non-climate KPIs such as fuel consumption and trip time.

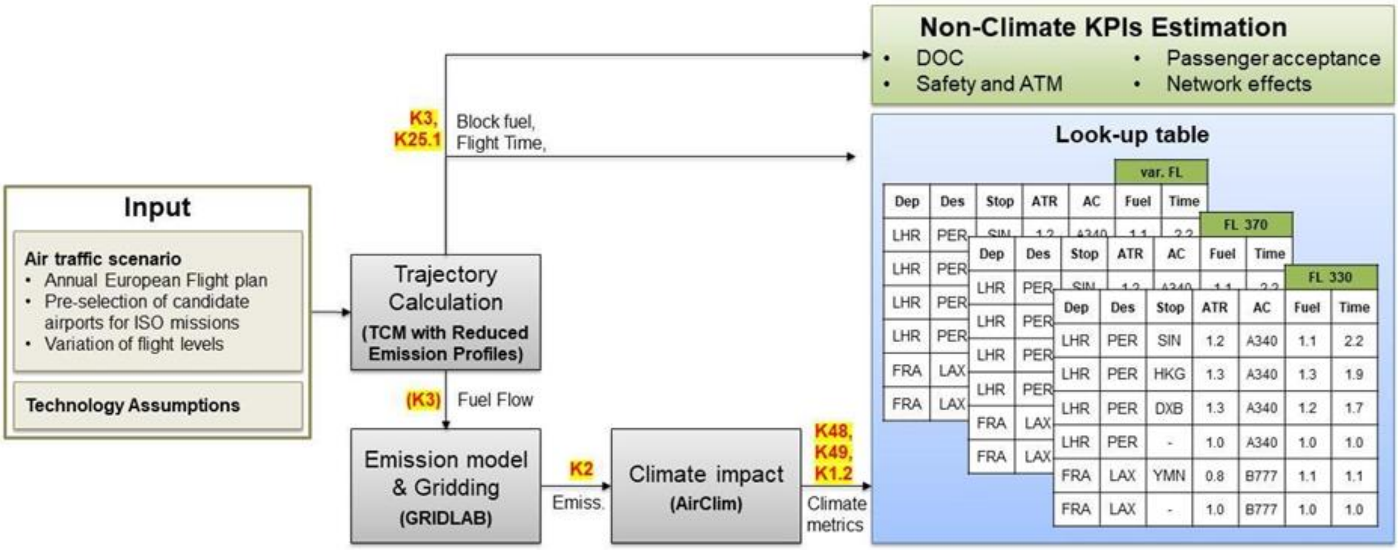


Figure 28. Model workflow for OI of ISOC

Input data is provided by an annual long-range European flight plan from Sabre Market Intelligence Database [17]. As ISO implementation is only expected to be beneficial for flight distances of more than 2500 nautical miles (NM), only long-range missions above this threshold are considered. For every combination of origin and destination (OD pair), a set of possible intermediate stop airport candidates is identified. These are derived from a global set of airports [44] and pre-selected according to detour (maximum 20% compared to the direct mission) and eccentricity (below 25%) of this airport along the great circle connection as well as regarding the resolution of the applied climate model AirClim to limit computational efforts. The approach of considering only one airport per AirClim grid cell significantly limits the number of airports to be considered (from approx. 400 possible ISO airports per OD pair to 9), but also simplifies the analysis in a way that it cannot be assured that the very best airport can be selected since only one per grid cell is considered. Besides different combinations of OD pairs, ISO airports and aircraft types, different flight levels are additionally considered to incorporate the effect of avoiding higher and more climate-sensitive altitudes. For this purpose, five different flight levels between 29000ft and 37000ft as well as a step-climb case are considered.

Calculating the trajectories for every mission (direct and non-stop) is the basis for assessing emissions and climate impact metrics for this OI. To do so, DLR's Trajectory Calculation Module (TCM) is used to create standardised reduced emission profiles (for details please refer to the previous deliverables). For each aircraft type non-georeferenced trajectories are calculated for discrete flight lengths in 100NM steps leading to the respective altitude and fuel flow profiles. The reduced trajectories are then adjusted and projected on the great circle between the respective OD pair. In this context, an average European load factor [34], great circle connections, average atmosphere conditions (International Standard Atmosphere, ISA) and BADA4 aircraft performance data are assumed [35].

Afterwards, the Global Air traffic emission distribution laboratory (GRIDLAB) is applied to generate 3D emission inventories for each flight of the described traffic sample. Based on the flight plan for each mission, the best-fitting reduced emission profile in terms of aircraft type and mission length is picked from the before-mentioned trajectory database both for the non-stop scenario and for both legs of the considered ISO missions. The selected trajectory is adjusted to the exact great circle distance between the two connected airports and their elevation. Emissions caused by taxiing and the take-off itself are considered following the landing take-off cycle (LTO) from ICAO, assuming the reference emission indices from the ICAO engine emission database [45]. Additional emissions and time are added for the on-ground time, i.e. emissions of the engine running in idle mode for 19 minutes are added for taxiing out, followed by 42 seconds in engine take-off mode. At the end of the trajectory, another emissions amount of 7 minutes in idle mode are attached, representing taxiing in. Finally, the emission profile is projected on the great circle between the connected airports, and the calculated emission amounts are distributed spatially on a numerical grid.

The GRIDLAB results for all relevant grid cells in terms of longitude, latitude, altitude in pressure unit, fuel burn, nitroxide emissions, and the aggregated distance for the derivation of contrail effects are fed into AirClim individually in the first step to simulate ATR20 and ATR100 for the different emission species as well as in total. A detailed description of AirClim can be found in [18][28][46]. It is assumed that an implementation of this OI starts 2025 and thus, simulations cover a period from 2025 to 2125 to assess ATR100.

To investigate implementation advantages and disadvantages from the Stakeholder's perspective, fuel consumption and trip time are used to derive pareto fronts (climate mitigation potentials as a function of allowed fuel and time penalties). In addition, these KPIs are used to estimate direct operating costs. Passenger acceptance is analysed based on a performed survey and implications on air traffic management (ATM) and safety are described qualitatively based on additional starts and landings as well as on selected flight levels during cruise.

Results

Assessment of climate KPIs

<u>Single-flight case study: Singapore – London (A380)</u>

To illustrate the approach of the described OI, a single mission case study is presented in the following. Based on the amount of ASKs covered, the mission from Singapore (SIN) to London Heathrow (LHR) with an A380 was selected. This flight is performed 1435 times in 2018 and covers approx. 7 billion ASK in that course, which makes it the most relevant one from the selected flight plan in terms of ASK.

A pre-selection of the candidate airports is performed as displayed in Figure 29. The first preselection step identifies all airports from the global sample that keep distance and eccentricity within the defined limits. In a second step, the sample is reduced according to the applied climate response model. This results in 17 considered ISO airports that are distributed over Asia, Europe, Africa and the Middle East with detours ranging from 0% to 18%.

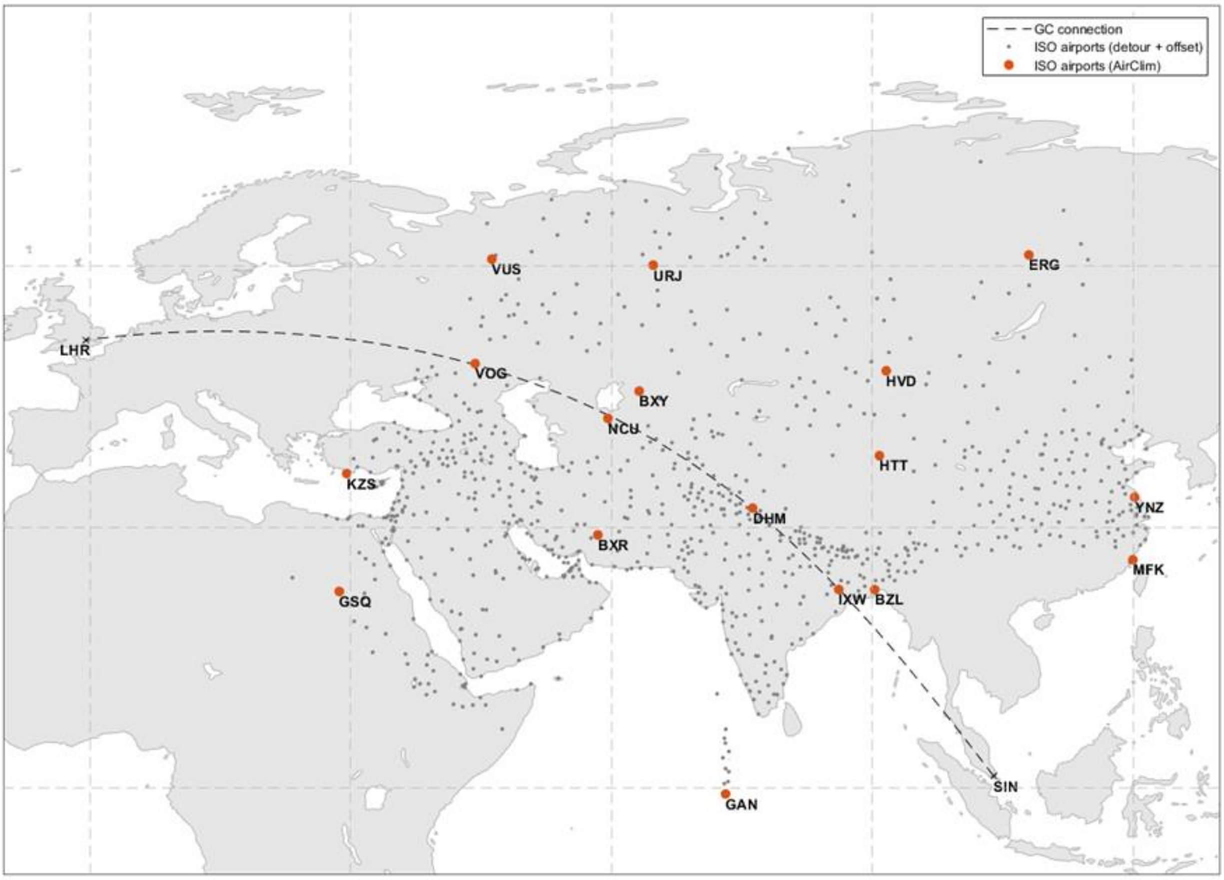


Figure 29. Location of selected intermediate stop airports (orange) according to the described methodology based on a sample of possible airports according to detour and eccentricity for a single-mission example from SIN to LHR.

Based on the selected airport, climate and non-climate KPIs are calculated according to the previously described modelling chain. An extract of the results is displayed in Table 35. In accordance with the results from the OI LOSL, it can be observed that a reduction of flight level leads to a reduction in average temperature response and an increase in fuel consumption. In addition, intermediate stopping reduces the fuel burn if optimal flight levels (i.e. step climbs) are assumed. However, this is associated with an increase in average temperature response. A combination of limiting flight altitudes and selection of intermediate stop airports according to climate-optimal criteria enables additional mitigation potentials.

Table 35. Overview on selected climate and non-climate KPIs in dependence of flight altitude and selected ISO airport (for a flight from SIN to LHR with an A380)

ISO airport	nonstop		DHM			BXR			IXW
CFL [100ft]	Step climbs	330	Step climbs	330	290	Step climbs	330	290	330
Detour [%]	-	-	0%	0%	0%	2.21%	2.21%	2.21%	0%
Eccentri-city [%]	-	-	8.73%	8.73%	8.73%	1.42%	1.42%	1.42%	21.8%
Fuel burn [t]	150.87	+ 8.73%	- 6.06%	+ 4.53%	+ 8.93%	- 3.84%	+ 6.68%	+ 11.1%	+5.64%
Emissions NO_x [t]	2.98	+ 14.1%	- 7.96%	+ 3.41%	+ 6.37%	- 5.84%	+ 5.38%	+ 8.27%	+ 5.87%
Flight Time [h]	12.70	- 1.36%	+ 4.79%	+ 3.34%	+ 4.71%	+ 6.80%	+ 5.37%	+ 6.77%	+ 3.48%
ATR20 [10^{-9} K]	9.41	- 29.4%	+ 6.24%	- 36.0%	- 44.3%	+ 5.19%	- 36.7%	- 45.0 %	- 35.4%
ATR100 [10^{-9} K]	6.11	- 30.0%	+ 6.26%	- 36.9%	-45.3%	+ 5.35%	- 37.4%	- 45.7%	- 36.2%

The selected example additionally shows that climate-optimal and fuel-optimal airports are not necessarily identical. While fuel-optimal ISO airports are typically closest to the centre point of the great circle connection (in absence of wind), the climate-optimal ISO airport can be associated with larger detours and eccentricities if the location of the trajectories is shifted to more climate-friendly regions. In this example, missions are shifted to more climate-friendly areas and thus climate-impact from non-CO_2 emissions (especially H_2O, NO_x and contrails) is reduced (see Figure 30).

Furthermore, the results illustrate that different mitigation levels can be achieved depending on acceptable levels of extra fuel and time. In contrast to the maximum mitigation potential of 46% for this flight, which is associated with an increase in fuel consumption by 11% and flight time by 7%, ATR100 can be reduced by 37% if allowable additional fuel burn and time are limited to 5%.

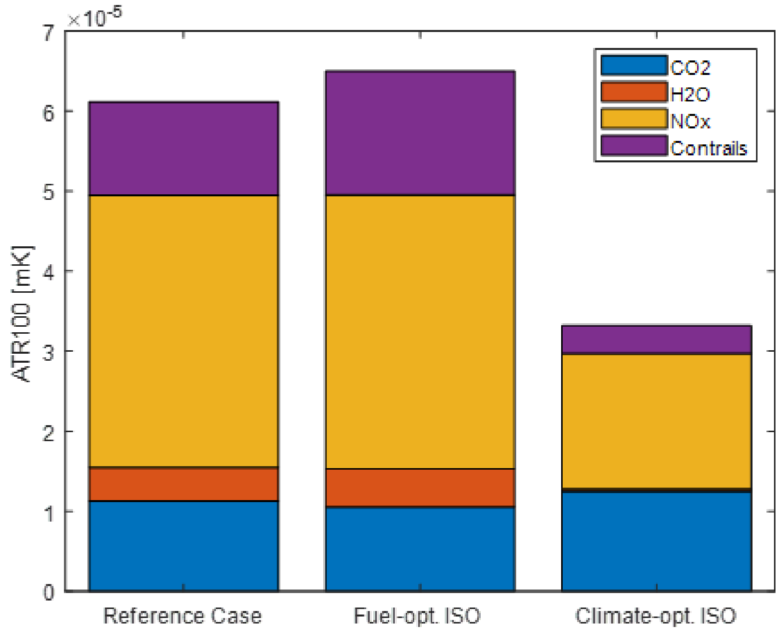


Figure 30. ATR100 for different emission species for the selected single-flight example

Aggregated climate mitigation potential

Based on the mitigation potential and ISO characteristics in terms of intermediate stop airport and flight level for each mission, results can be aggregated to determine absolute climate mitigation potentials.

An implementation of ISOC as a combination of climate-optimal selection of intermediate stop airports and consideration of different flight levels shows a significant climate-mitigation potential of 40% in ATR100 (and 39% in ATR20). The absolute mitigation potential is 6.93 mK (ATR100), respectively 10.39 mK (ATR20)8. This significant reduction in climate impact can mainly be explained by a reduction in contrail (- 52%) and NO_x effects (- 49%) due to the changed routes, weights and altitudes. ATR100 induced by water vapor is furthermore reduced (- 90%). This overcompensates an increase in CO_2 effects (+ 18%) caused by longer detours and less fuel-efficient flight levels (Figure 31).

However, this is associated with substantial changes in non-climate KPIs. Fuel consumption increases by 18% and trip time by 10% in this context, which limits applicability of this OI from a Stakeholder's point of view. On the other hand, a fuel-optimal implementation increases fuel efficiency by approximately 2%, while trip time is extended by 3% on average. The small extra time is due to the fact that ISO airports are preferred that are closes to the centre of the great circle connection between origin and destination. This is typically associated with minimum detours and thus minimum flight time extension. Nevertheless, the fuel-optimal ISO concept is not beneficial from a climate perspective, as ATR100 is increased by 1%.

[8] For the summary of absolute ATR20 and ATR100 we assume a linearization of climate impact, which represents an estimation. Detailed calculations considering saturation effects will be subject to further work following this deliverable.

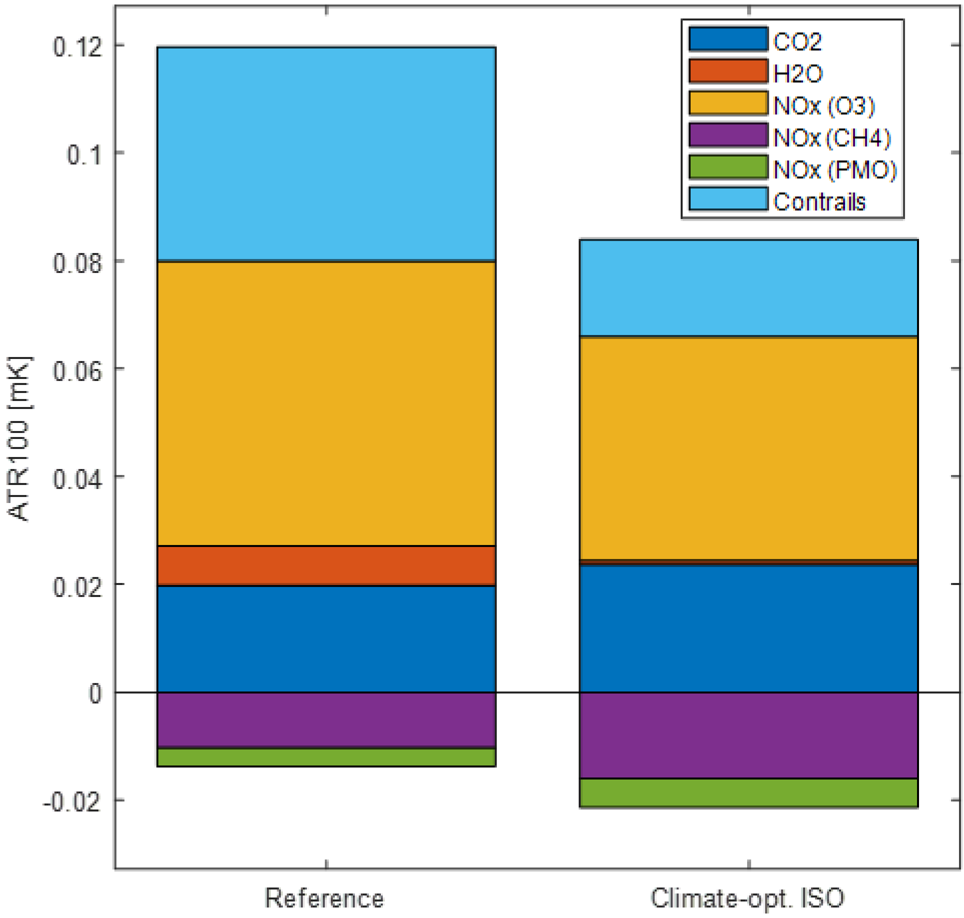


Figure 31. ATR100 for different emission species (full scope)

A combination of both effects can be covered by calculating pareto fronts for different levels of allowed extra fuel and time. Results are displayed in Table 25. Limiting extra fuel and time still enable significant climate mitigation potential while ensuring applicability from an operator's perspective. For example, a limitation of extra fuel and time to 10% compared to the reference case enables a reduction of ATR100 by 25%. While there are a lot of ISO options selected for high allowed penalties, especially strict limits in flight time, the available ISO options as these are always connected to an extension of flight times. This offers the opportunity to configure pareto fronts in a way that ISOC is only implemented if it is also beneficial from a fuel efficiency perspective (Table 36). If no additional fuel consumption is allowed but flight times can be extended by 10%, this leads to a fuel saving potential of 0.2% and a reduction in ATR100 by 6%.

Table 36. Estimation of increase direct operating cost, depending on pre-defined fuel and time penalty for climate-optimal ISO

Fuel penalty	Time penalty	ISO share	ATR100
-	-	100%	- 40%
10%	10%	90%	- 25%
5%	5%	17%	- 5.0%
1%	1%	0%	0%
0%	10%	30%	- 6.0%
0%	5%	8.3%	- 2.4%

In contrast to the fuel-optimal specification of ISO, generally more missions are beneficial for implementing ISO from a climate perspective (almost 100% for climate-optimal and approximately 50% of all missions for the fuel-optimal configuration). Also, it can be confirmed that climate-optimal ISO is also beneficial for shorter great circle connections in comparison to missions where ISO is beneficial from a fuel-efficiency perspective. Furthermore, detours and offset factors for ISOC are higher than for the fuel-optimised counterpart, because non-CO_2 impact offset fuel efficiency effects for a large share of the analysed missions.

Assessment of non-climate KPIs

The following section focuses on the Stakeholder impact resulting from an implementation of climate-optimised ISO. For this purpose, the analysis is focussed on the following main Stakeholders and associated KPAs and KPIs:

- Airlines: Fuel consumption, Flight time, Network effects, Direct operating cost (Economic assessment)
- Air traffic control: Air traffic controllers' workload, additional utilisation of ISO airports accident rate airborne and on-ground (ATM, airport capacity and safety assessment)
- Passengers & Society: Passenger acceptance (Acceptance assessment)

Based on the results achieved in simulation of climate impact, a detailed qualitative description of effects of an implementation of ISOC on the different Stakeholders is followed by a quantitative estimation of the described KPIs.

Economic assessment

- In terms of costs, an intermediate stop-over, an additional jump to bring passengers and cargo from A to B, when previously was performed with direct flights, is associated with the following additional efforts:
- Increased operational times imply increased operating costs for flight and cabin crews.
- Maintenance costs increase as the airframes will be subject to an additional number of jumps.

- Airport fees and ANSP charges increase as additional starts and landings are performed at intermediate stop airports in contrast to the reference case.
- In those cases, where intermediate stop mission is associated with higher fuel consumption, fuel costs increase as well as carbon trading charges from more CO_2 emissions (CORSIA, ETS).

Restricting fuel and time penalties to certain limits, enables considerations on different levels of cost increase for the stakeholders, especially for the airline operating the flights. Based on an FAA estimation on direct operating cost composition [18], the following increase in Direct Operating Cost (DOC) can be estimated. Limiting additional fuel and flight time on the level of individual flights shows that on average, additional fuel and flight time are significantly below those penalty limits. Details are displayed in Table 37. A more detailed analysis of direct operating cost changes and the general economic impact of this OI should be subject to further investigations following this study.

Table 37. Non-climate KPIs of ISOC in dependence of different fuel and time penalties allowed

Fuel penalty	Time penalty	Extra fuel average	Extra time average	Add. stops	ATR100	DOC impact
-	-	+ 18%	+ 9.6 %	+100%	- 40%	High
10%	10%	+ 5.5%	+ 6.3%	+90%	- 24%	Medium
5%	5%	+ 0.3%	+ 1.0%	+17%	- 5.0%	Low

Besides direct additional efforts and resulting rises in operating cost resulting from increased flight time and fuel consumption, implementation of ISO also impacts the airlines network. Among others, longer trip times due to refuelling stops can require adjustments to the network. Furthermore, additional destinations can be reached within the network due to intermediate stops. An enhancement of the concept can be considered if passengers will also be allowed to board and de-board at the respective intermediate location. Dependencies between ISO and network effects are further described in Section 2.4.

ATM, airport capacity and safety assessment

As mentioned in LOSL, a limitation of flight altitudes to reduce climate impact and injecting the same load of traffic in a reduced airspace would imply an overconcentration of traffic in the same airspace volumes. Consequently, ATFM delays can be enforced. A detailed quantitative analysis of changes in airspace utilization due to flight level adjustments is not determined with this study as the modelling workflow excludes day-specific ATM or weather-related restrictions as the focus is set on an aggregated annual scale. Details on ATM-related impacts of flying lower can be found in Section 2.1.

Furthermore, refuelling in a remotely located airport, implies a landing itself, and as per ICAO rules, alternate airports should be available. Probability of accidents rises with the number of additional starts and landings. The fact of adding one stopover per oceanic and long-haul continental routes, implies to perform two times the number of landings and take-offs on an ISO mission (as displayed in Table 26). This leads to an increase of landing and take-offs by 17 % in the 5% penalty case and by 100% if maximum mitigation potential is realised, which increases the inherent levels of risks associated compared to non-stop operations.

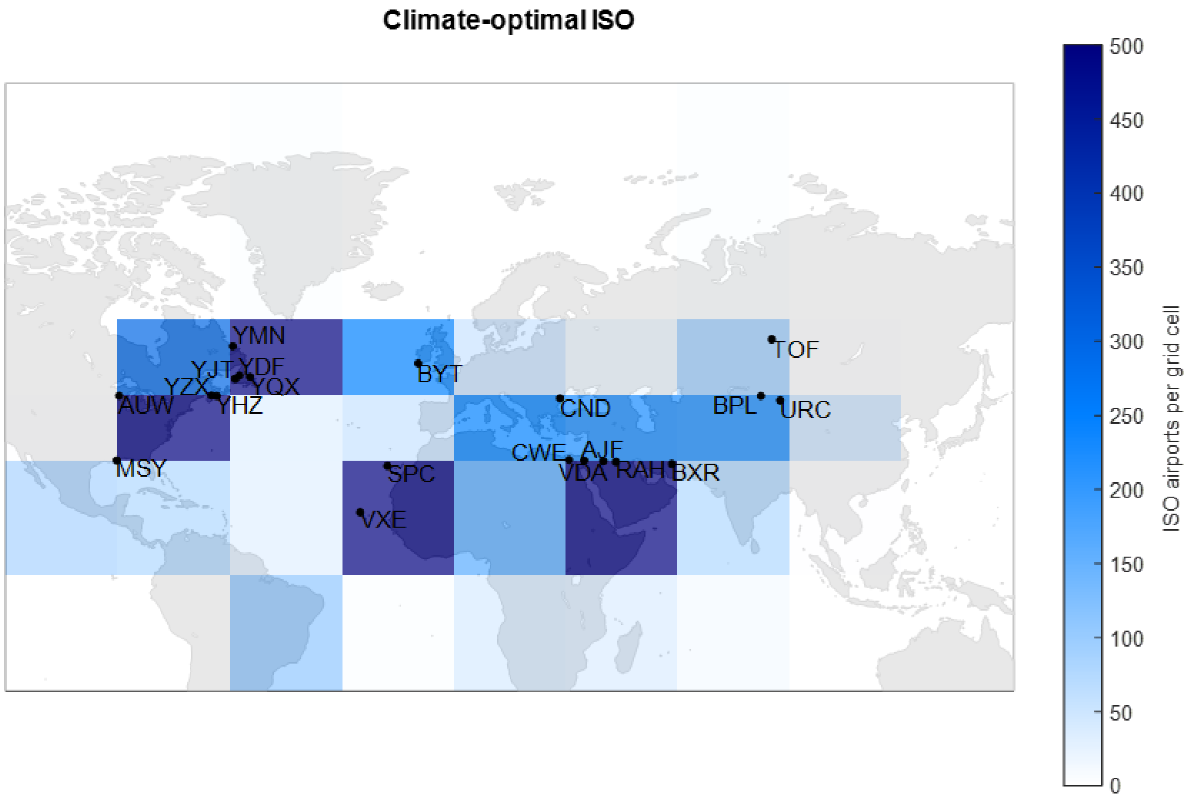
In addition, ISO affects the frequented ISO airports in terms of utilisation but also in terms of required infrastructure (e.g. regarding fuelling capacities) if this concept is implemented. In this context, an analysis of the frequencies as the selected airports is required. Figure 30 illustrates the location of the selected intermediate stop airports according to the resolution of AirClim. It shows that there are locations that are especially attractive for ISO from/to Europe. In contrast to the fuel-optimal scenario where ISO airports are typically close to the great circle connection, climate-optimal ISO airports are generally located more towards the equator, avoid the polar region and come along with longer detours in general.

Based on the performed analysis, a large amount of intermediate stops will be performed at a limited number of airports, leading to an additional congestion at these airports. Figure 32 highlights the twenty most frequented airports if climate-optimal ISO is implemented for European long-haul flights. For some of the selected airports, this leads to an additional utilisation of more than 100% which can probably not be handled without significant infrastructure adjustments. This is partly influenced by the chosen methodology to pre-select airports to consider for ISO. However, a broader distribution over airports close to the selected one is possible and needs to be considered when aiming for a realistic implementation of the ISO concept.

Acceptance assessment

From the passenger point of view, it needs to be considered that as of today, flying from Europe to Australia takes about one full day, just short of 24 hours in the fastest way, with one stop. If more stops are required due to an implementation of intermediate stop operations, the length will become much longer and possibly affect passengers’ acceptance.

The passenger acceptance was investigated by a survey where the interviewees were asked about their stance to a flight that is interrupted by one or two quick intermediate stops only for refuelling. 33.5% were in favour with that concept, another 37.9% had a neutral opinion on that and 28.6% were not in favour with climate-optimised ISO. A second question expands the concept of ISOC by a temporal extended intermediate stop that allows passengers to leave the aircraft and even explore the city of ISO airport. 43.4% were generally in favour with that operational concept, and 23.6% disliked the idea that the travel time would increase by far. Another third of interviewees had a neutral attitude towards a longer intermediate stop to explore the city.



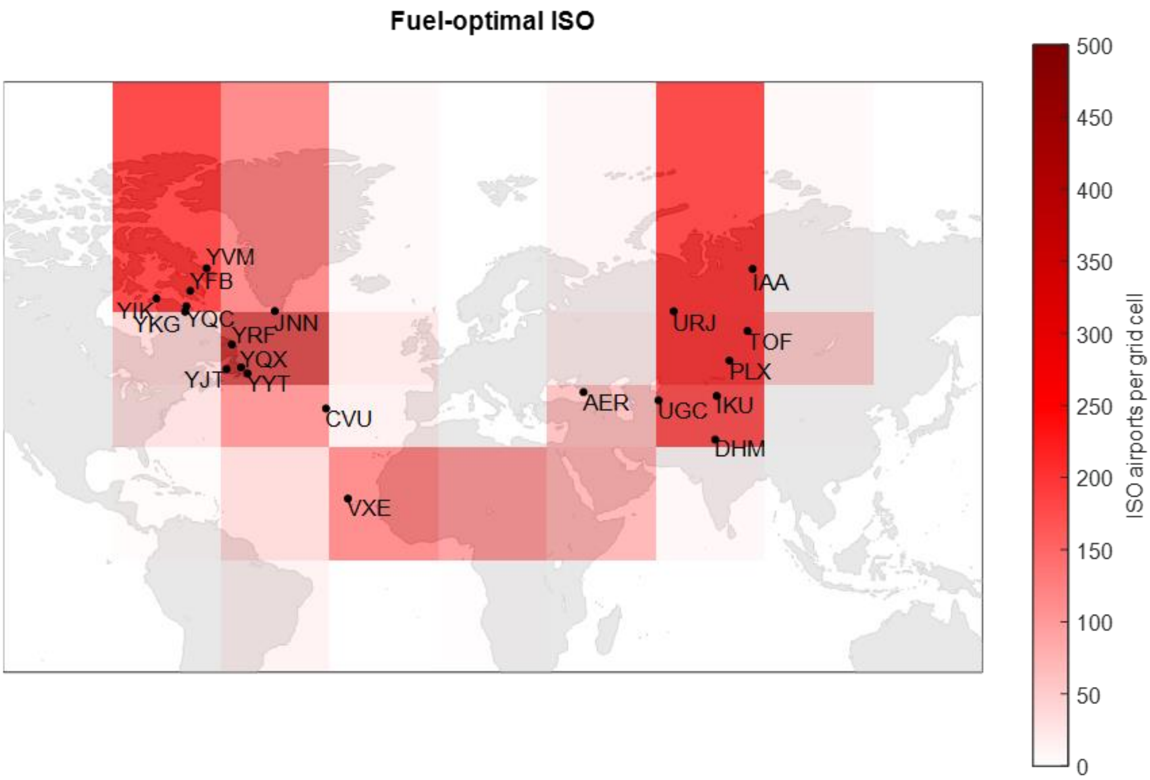


Figure 32. Distribution of intermediate stop airports over considered grid cells (top: climate optimised ISO, bottom: fuel-optimised ISO)

Uncertainty estimate

For a reliable assessment of implementation impacts of this OI, an investigation of uncertainties incorporated in the modelling and simulation approach need to be considered. Two major categories of uncertainties were defined and described regarding their impact in the following.

Study and flight plan set-up

As previously mentioned, the pre-selection of candidate airports considered in the ISO flight plan is limited to one airport per mission and AirClim grid cell. On one hand, this simplifying assumption helps to limit computational efforts and keeps the investigation of intermediate stop airports manageable. On the other side, the selected ISO airport is not necessarily the climate-optimal one but an optimised one from the sample of pre-selected airports. To investigate the uncertainties resulting from that, a separate sensitivity study is recommended following this deliverable.

The same holds true for the pre-selected flight levels that are considered and subject to comparison within this study. A more detailed investigation of different flight levels considering realistic weather data can be found in Section 2.1.

Trajectory and emissions modelling uncertainties

In the process of remodelling flight trajectories and emissions, assumptions were made that have an influence on the results achieved. The analysis was focussed on the major sources of uncertainty, that are:

- Assumption of an average European load factor: To facilitate calculations without detailed TOW data information, an average payload per aircraft and a fuel planning approach aiming for maximum fuel efficiency was assumed. However, different approaches and different load factors are realistic on different flights, so that varying take-off masses are more realistic. This uncertainty was quantified by different load factors of a global air traffic sample and compared the resulting emission totals of the generated emission inventory. The seat load factor of each flight within the global flight plan that initially follows continental average values in the reference simulation is enhanced by 5 and 10 percent points and reduced by the same values in the course of the sensitivity study. The results show that an enhancement of all seat load factors by 5 percent points leads to higher CO_2 (+ 1.2%) and NO_x emissions (+ 1.7%) on a global scale compared to the reference scenario. Increasing all load factors by even 10 percent points results in 2.4% higher CO_2 and 3.5% higher NO_x emissions. Shrinking the load factors by 5 (10) percent points will reduce the total CO_2 emissions by -1.2% (-2.3%) and NO_x by -1.7% (-3.2%).
    - Consideration of great circles: A similar sensitivity study with an emission inventory based on a global flight plan investigated how emission distributions and totals change if additional arrays of trajectories are scattered around the great circle route and scaled with their detour for each OD pair. The results show that a global mean of trajectory inefficiency of 3.5% lead to an increase in CO_2 emissions by 2.9% and NO_x emissions by 2.6%.
    - Consideration of average atmosphere conditions and no wind: Assumptions on atmospheric boundary conditions were made to enable an analysis of an annual flight plan as defined for all network-related OIs. For ISOC, ISA was applied, so that no wind was considered in the analysis. A sensitivity study with a one-year wind field from ERA

Interim data for the year 2012 applied on the global emission inventory shows that the effects of an annual wind statistic increase the air distance on global average by 3.4% compared to the ground distance. In an annual and global mean, losses due to headwinds cannot be compensated by gains due to tailwinds. The relative emission changes compared to the reference emission inventory are similar to the detour sensitivity study: +2.8% for CO_2 emission total and +2.5% for NO_x emission total.

- Assumption of BADA4 performance data and ICAO Emission indices: To model aerodynamic and engine performance data along the flight trajectories, BADA4 performance data was utilized in this study.

Climate impact modelling uncertainties

High accuracy of determining climate impacts from different species and their partly counteracting effect is required to reliably assess the mitigation potential of the different OIs. A Monte-Carlo simulation approach has been applied in [26] to assess reliability and uncertainty of non-linear climate chemistry response model AirClim. It was shown that even small differences in emissions can be considered and the resulting changes in climate impact from different mitigation options can be assessed.

Comparability of the results with the other OIs

Based on the analysis, results can be scaled to an aggregated European scenario. However, an extrapolation needs to be performed with care since results have only been calculated in detail for the selected scope and assumptions. In accordance with the defined full scope of ClimOP (European aviation in 2018), the geographical scope of this study was set to all flights from and to the ECAC area and the temporal scope included all flights of the year 2018.

Besides that, additional restrictions taken in course of the modelling process need to be considered in terms of comparability and harmonisation of OIs:

- Restriction to long-range flight plan: An implementation of ISO is only feasible for long-range flights. Therefore, the scope of this study excluded short-range flights below 2500 NM. The assumption of no additional mitigation potential for ISO on short-range flights, can be used for scaling purposes.
- Restriction of aircraft types: This analysis is limited to the most relevant aircraft types regarding the ASK covered by the respective fleet, i.e., 97.7% of all European long-range ASK are covered (Figure 31). It can be assumed that climate mitigation by ISOC can be transferred and scaled to the remaining aircraft types as well.

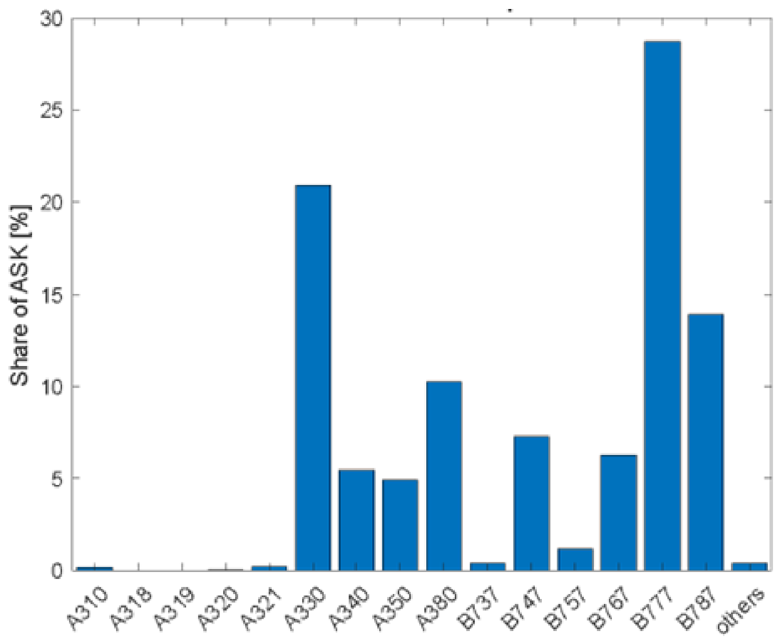


Figure 33. ASK per aircraft type for European long-haul operations in 2018

Based on the assumptions taken, it is possible to scale the results of this study to an annual European scope by using the ASK covered. For this purpose, results can be scaled to all aircraft types operating on European long-range missions in 2018. As no ISO effect is expected for short-range flights, no additional scaling is required, though relative mitigation potentials need to be adjusted towards a full European flight plan.

Applicability of the OI

An implementation of ISOC accompanies a couple of adjustments to the air traffic system. To enable ISO on European long-haul flights, the available intermediate airports need to handle the additional amount of starts and landings. In some cases, the required infrastructure needs to be upgraded. Furthermore, airline networks require adjustments to be enabled to incorporate the additional stops. From an aircraft operator perspective, this OI, like others in this ClimOP project, implies a paradigm change for aircraft operation, and therefore there will be a regulatory and standardisation change that will represent a big socio-economic impact for the aviation community.

Equivalent to LOSL (see section 2.1 and appendix A.1), a higher utilisation of climate-friendly flight altitudes in this context leads to an additional utilisation of these flight levels. Consequently, an upgrade of CNS infrastructure will facilitate an implementation of this OI.

Furthermore, ISOC aims to reduce the climate impact in general, which is not in line with the currently implemented carbon trading schemes that focus on climate impact from CO_2 emissions only. If ISO is implemented to minimise ATR, higher CO_2 emissions can be accepted if climate impact from non-CO_2 emission is mitigated more at the same time. Considering non-CO_2 emissions in regulations and policies will support ISOC.

Conclusions

To sum it up, this study proves a significant climate mitigation potential from climate-optimised ISO. The study confirms that ISO can be adjusted to benefit the climate response from aviation in addition to a fuel-optimal configuration. For this purpose, two key components determine the OI: (1) The selection of the intermediate airport is performed based on climate optimal criteria instead of based on minimum associated detours. (2) Flight altitudes are limited either (a) to a constant flight level or (b) selected on climate-optimal criteria to avoid climate-sensitive altitudes. The resulting mitigation effects range between 24% and 40% for a climate-optimal solution and between 2% and 25% if extra fuel and time are limited to certain extent. In this context, also differences between climate-optimal and fuel-optimal specifications of ISOC were identified in terms of detour, eccentricity and location of refuelling airport as well as regarding flight time, fuel burn and climate impact.

An estimation of the Stakeholder impact is provided in this study. Changes in non-climate KPIs, such as fuel burn, flight time and number of landings as well as flight altitudes do not only influence operating cost, but also airspace and airport capacities as well as passenger acceptance. To facilitate an implementation of ISOC, adjustments in infrastructure as well as regulatory incentives should be implemented.

A.6 Single engine taxiing / E-taxi and hybrid

The goal of this assessment is to determine what the potential savings of alternative taxiing are on a global, European and local level, using Milan Malpensa.

The key hypothesis is that larger airports are more likely to have large savings, due to longer taxi times and more traffic. Also, medium sized jets are the most likely candidates, as most of the flights are performed by these and these are used throughout the day, where large, long range aircraft are not.

The data use for assessing this AI is:

- A peakday extracted from a global OAG timetable for 2018 [47]
- Taxi times for 2018 published by Eurocontrol [48]
- ICAO Fuel and emissions data for aircraft extracted from the Aviation Environmental Design Tool (AEDT)[49] [50]
- Estimated for APU fuel consumption published by ICAO [51]

For simplicity, four different aircraft types are modelled with respect to fuel consumption:

- The Embraer 190 represents all Embraer E-jets and Airbus A220's
- The Airbus A320-200 represents all A320 family aircraft, including the NEO.
- The Boeing 737-800 represents all B737 aircraft including the Max.
- The Airbus A350-900 represents a twin engine wide body aircraft. All regional and four engine widebody aircraft were not considered.

Figure 34 illustrates how this data was combined into a table of fuel and emissions values changed per aircraft type and airport.

To get an upper bound on what the savings could be, the workflow in figure 35 shows how this was combined in a global analysis, determining the maximum possible savings that could be achieved and the number of tow trucks required to achieve this. It should be noted that this estimate is somewhat unrealistic as some tow trucks at some airport would not be utilized enough to make any economic or environmental sense.

In the final analysis, performed for Malpensa, an optimal assignment model was used, which then plans and assigns tow trucks to flights. An important parameter is that each additional tow truck used throughout the day must offset a minimum amount of fuel, which was chosen at 500kg in the basis. Figure 36 illustrated the workflow for the optimization.

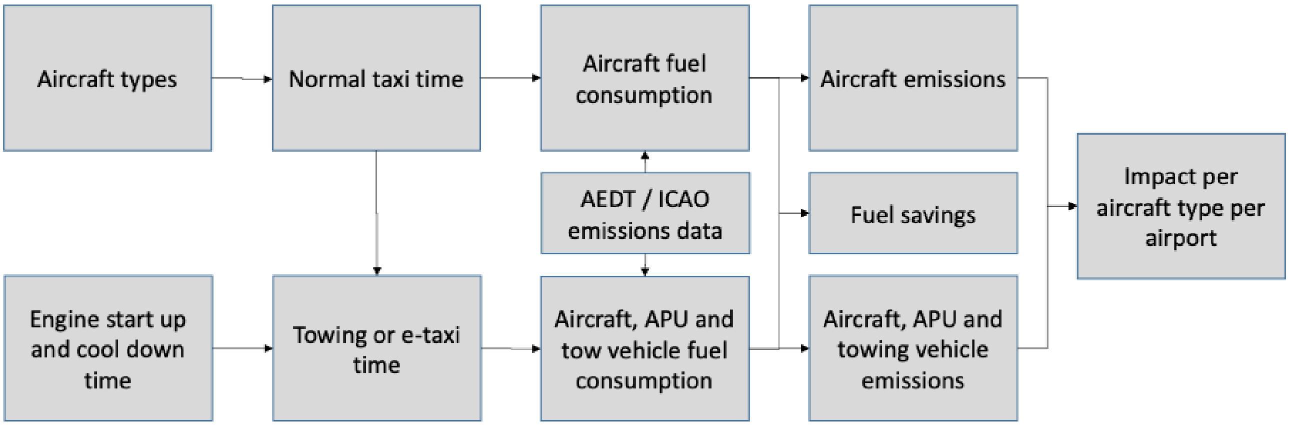


Figure 34: Workflow determining impact numbers per aircraft type and airport

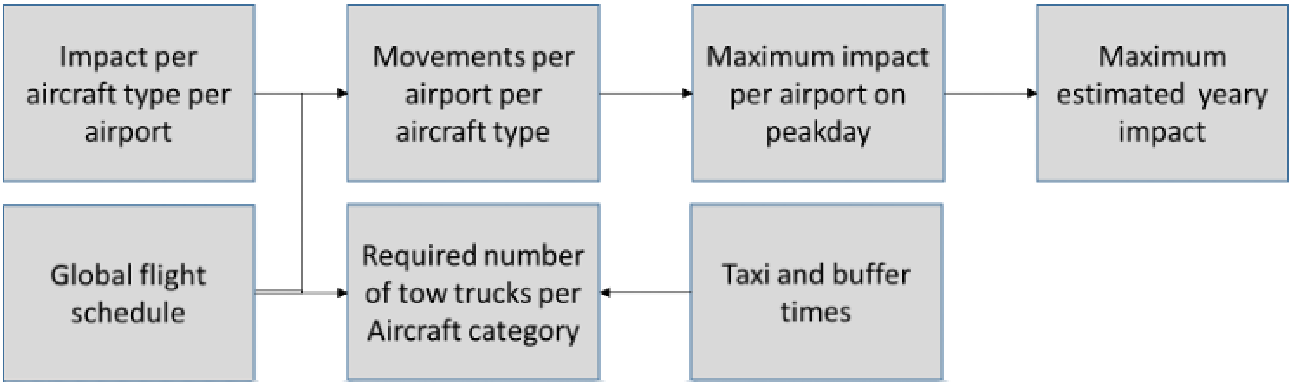


Figure 35: Determining maximum total impact of introducing towing

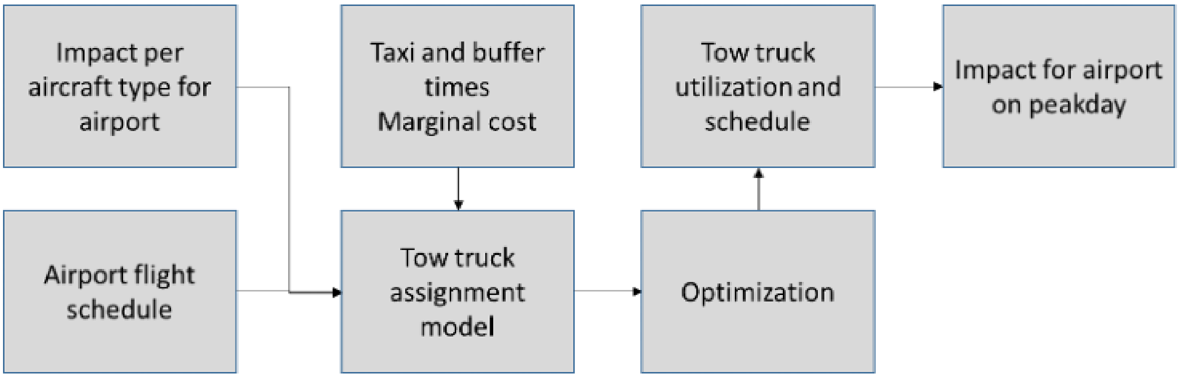


Figure 36: Tow truck assignment optimisation workflow

Fuel consumption

For an Airbus A320 at Malpensa (MXP), which has an average taxi time in time of 6.02 minutes and a taxi out time of 13.46 minutes, normal taxying, burning 0.102 kg/sec of fuel per engine, will result in a fuel consumption of 73.7 kg on taxi in and 164.7 kg on taxi out.

For Single engine taxiing, we assume the first two minutes of taxi in and the last three minutes of taxi out are performed with both engines running. On a single engine, the engine will be consuming 25% less fuel than with both engines running. This means an A320 on taxi out will consume 96.0 kg using one engine and 36.7 kg using both engines, a total of 132.7 kg, which is 32 kg less than using a normal taxi out. For taxi in, the saving is 12.3 kg.

For towing on taxi out, we need to have the APU running which shuts down 3 minutes before take-off. The APU of an A320 consumes on average 100kg/hr, resulting in 17.4 kg on taxi out at MXP. Assuming the engines are running the last 4 minutes of taxi times, still 49.0 kg of fuel is used. Assuming 200kW of power used on average by the (electric) tow truck, this means 63 kWh of energy used until the engines are running. Assuming a 30% efficiency and 43MJ/kg this would result in a fuel usage of the tow truck of 5.3 kg of fuel 6.4 or litres of fuel.

The main KPI's that have been assessed are fuel consumption and the number of towing trucks required, both by the aircraft engines as well as the APU, which is currently required to be running during towing. Fuel consumption is converted to CO_2, CO, HC and NO_x. PM2.5. PM5 and PM10 are currently not calculated and can only be estimated as a function of the other emissions.

For not climate KPI's, currently only the number of tow trucks, representing the investment costs are considered. While acceleration is somewhat reduced, impact on taxi times cannot yet be accurately predicted, though the impact on overall taxi times is considered to be minimal. One issue that is being researched by the AEON project is the impact of attaching and detaching the towing vehicles near the runway on congestion.

Climate Impact of operational towing

Below, Table 38 indicates the reference value for the fuel consumption of aircraft while taxiing. Lower medium (LM) are larger region jets, such as the Embraer 170-190 series and the airbus A220, upper medium (UM) jets are 737 and A320s and heavy twins (H) are all 767, 787, 777, A330, A350's.

Table 39 calculates the values for using single engine taxiing, assuming the last 4 minutes of taxi out and first 3 minutes of taxi in the both engines need to be running. For single engine taxiing, the single engine is assumed to be running at 150% fuel flow, meaning 75% fuel flow during normal taxi. The emissions values for single engine taxiing are assumed to be half way between the ground idle and the approach values. This causes CO and HC values to be much lower, but NO_x values to be slightly higher than in the reference scenario.

Table 40 gives the maximum values of implanting towing at all airports in the European region, for all airports in ICAO regions E and L, assuming 2018 traffic levels. To get the yearly levels, it was assumed that the average day will have 80% of the movements of the peak day, meaning that the yearly totals are 0.8*365 times the value of the peak day. It is assumed that towing will be performed electrically.

Table 41 shows the number of towing vehicles required for this for the top 25 airports and the total for all 295 airports in the analysis. If we divide the values in table 3 by the number of tow trucks, we find that the average LM truck saves 1520 kg of fuel, the average UM truck 1120 kg of fuel and the average heavy truck 755 kg of fuel. While this might seem reasonable, many of these trucks would be under-utilised, and thus would not offset their production impact, especially of only towing vehicles on taxi in which tends to be much shorter and thus fuel saving.

Table 38: Fuel consumption in European region for normal taxiing

	Fuel [kg]	CO_2 [kg]	CO [kg]	HC [kg]	NO_x [kg]
Lower Medium	835,163	2,639,114	17,923	860	3,683
Upper medium	3,509,867	11,091,180	109,342	6,282	14,980
Heavy twins	244,722	773,322	10,212	984	903
Total Peak day	4,589,752	14,503,617	137,477	8,126	19,566
Year estimate	1,340,207,565	4,235,056,022	40,143,174	2,372,917	5,713,249

Table 39: Fuel consumption saving with respect to normal taxiing in European region for single engine taxiing

	Fuel [kg]	CO_2 [kg]	CO [kg]	HC [kg]	NO_x [kg]
Lower Medium	165,272	522,258	8,574	423	-935
Upper medium	649,373	2,052,020	47,579	2,860	-1,772
Heavy twins	44,667	141,149	4,391	442	-120
Total Peak day	859,312	2,715,427	60,544	3,726	-2,826
Year estimate	250,919,231	792,904,791	17,678,738	1,087,882	-825,272
Saving	19%	19%	44%	46%	-14%

Table 40: Fuel consumption savings w.r.t. normal taxiing in European region for towing

	Fuel [kg]	CO_2 [kg]	CO [kg]	HC [kg]	NO_x [kg]	Energy [kWh]
Lower Medium	656,569	2,074,757	15,681	753	3,222	-69,752
Upper medium	2,617,426	8,271,065	92,308	5,305	12,640	-1,573,684
Heavy twins	176,891	558,977	8,558	824	757	-129,476
Total Peak day	3,450,886	10,904,799	116,548	6,882	16,618	-1,772,912
Year estimate	1,007,658,611	3,184,201,297	34,031,909	2,009,649	4,852,360	-517,690,274
Saving	75%	75%	85%	85%	85%	

Table 41: towing vehicles required to tow all flights in European region

	LM	UM	H	Tot
AMS	22	42	15	79
CDG	17	43	15	75
FRA	10	52	10	72
MAD	8	41	14	63
FCO	6	47	8	61
LHR	2	39	19	60
MUC	10	42	6	58
BCN	2	45	8	55
LGW	4	40	6	50
BRU	4	39	6	49
ZRH	10	27	9	46
DUB	11	26	6	43
PMI	4	36	1	41
IST		27	12	39
ATH	3	32	3	38
DUS	5	28	4	37
LIS	8	26	3	37
ORY	2	32	3	37
HEL	4	27	5	36
OSL	2	29	4	35
CPH		29	5	34
MXP	***6***	***23***	***5***	***34***

TXL	3	29	2	34
VIE	3	29	2	34
ARN	1	27	4	32
All	**432**	**2338**	**234**	**3004**

Tow truck effectiveness for Malpensa

Figure 37 shows how many trucks would be needed at Malpensa throughout the day for the three categories of aircraft, including both taxi out and taxi in. As ca be seen, there are quite a few peaks which drive the number of tow vehicles required to tow all of the aircraft.

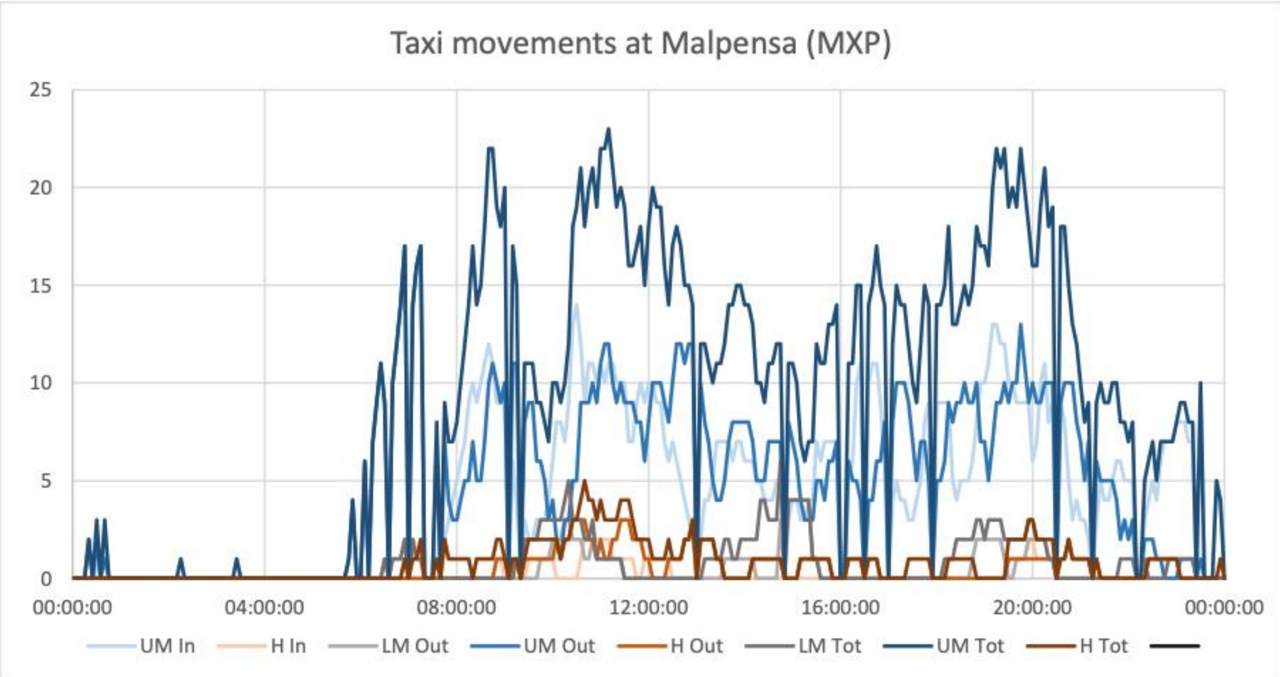


Figure 37: Towing vehicles required assuming 20 minute buffer between tows

The marginal costs a truck must offset is an important parameter to determine the number of tow trucks that need to be deployed to get realistic fuel savings. Figure 5, 6 and 7 show the effect of the marginal cost per tow truck on the number of towing vehicles deployed, the total fuel savings and the average fuel saving per truck. Results for Amsterdam airport (AMS) are included in the appendix.

Using a (low) estimated value of €1 million for a tow truck and a 10-year lifespan, the depreciation of the truck would amount to €274 per day. This does not include other operating costs such as energy and staff. Ideally the trucks would be autonomous to reduce not only staff costs but also recruitment.

Assuming a fuel price of € 0.90 per kg, a marginal cost of € 500 would seem a reasonable value. Illustrated in table 42, for MXP, this would mean a decrease in fuel savings of only 3.2 tons (from 33.2 to 30.0 tons), while reducing the total number of tow trucks needed by 16 (from 34 to 18). The average fuel savings per truck then goes up from 976 to 1657 kg per truck.

Table 42: Effect on climate impact of increasing the required marginal fuel saving per towing vehicle at MXP

	Tow trucks	Fuel [kg]	CO_2 [kg]	CO [kg]	HC [kg]	NO_x [kg]
10 kg	34	33191	104883	1181	71	166
500 kg	18	29830	94262	1043	61	150

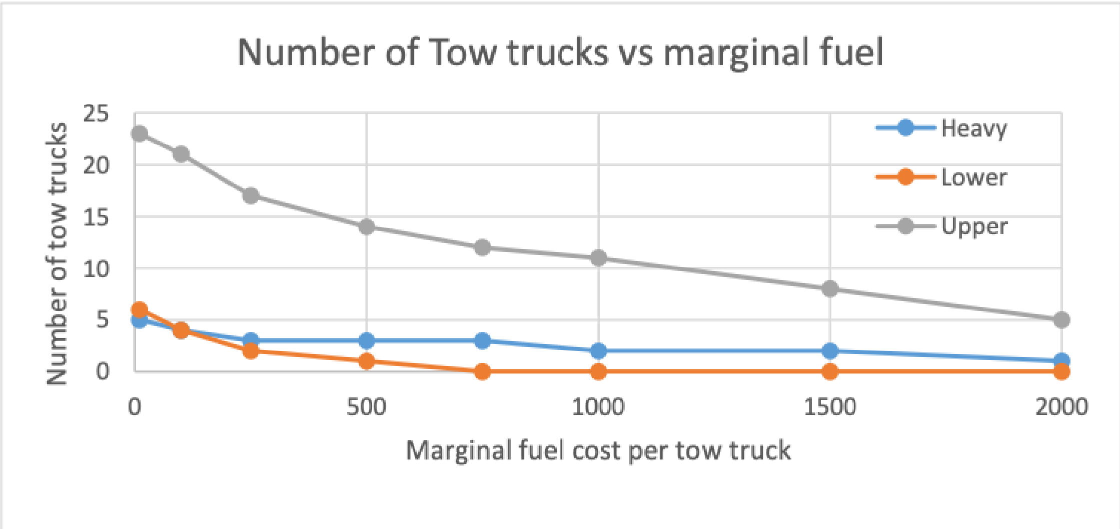


Figure 38: Tow trucks vs. marginal fuel per truck cost for MXP

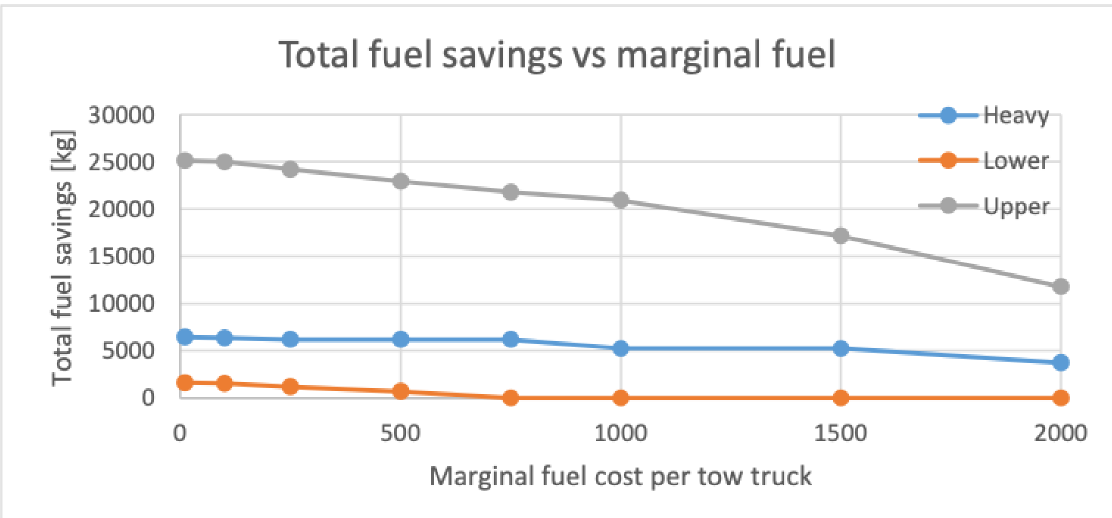


Figure 39: Total fuel savings vs. marginal fuel cost per truck for MXP

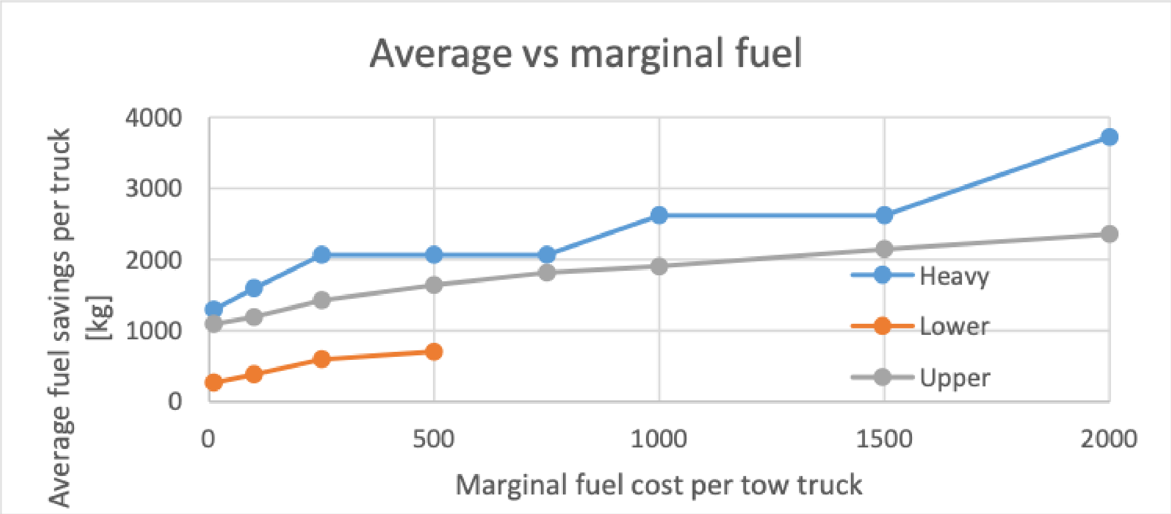


Figure 40: Average fuel savings per truck vs. marginal fuel cost per truck for MXP

Sensitivity analysis

Two main uncertainties regarding the towing of aircraft remain, next to the operating costs of the tow truck and the cost of fuel. These are the scheduled time needed between towing two aircraft and the time needed for the engines to be running before take-off and after landing.

The required buffer time has two components. The first component is the time for the tow truck to reposition from one flight to the next. The other is robustness of the schedule with respect to delays. In the conducted study, the buffer was assumed to be 20 minutes, however this might not be enough for the larger airports and could be lower for the smaller ones. Figures 41 and 42 show the impact on the MXP case assuming a 500 kg marginal fuel requirement for each truck. More tow trucks are needed, while the savings are only slightly impacted when the buffer time increases. More research should be done to estimate appropriate buffer times and rescheduling in case of delays. A complication with this is that fuel for taxi out needs to be accounted for in flight planning, so last-minute changes could have a significant impact.

Another uncertainty is what the applied Engine Start Up Time (ESUT) up and Engine Cool Down Time (ECDT) times are that will be used in reality. If engines are not warmed up enough before take-off or cooled down after landing, this can result in increased wear and thus maintenance. For the analysis and ESUT of 4 minutes and ECDT of 3 minutes was assumed. Figure 43 shows that increase of the ESUT (and change ECDT by the same amount of time) reduces the effectiveness of towing and significantly reduces the total fuel savings, as shown in figure 44.

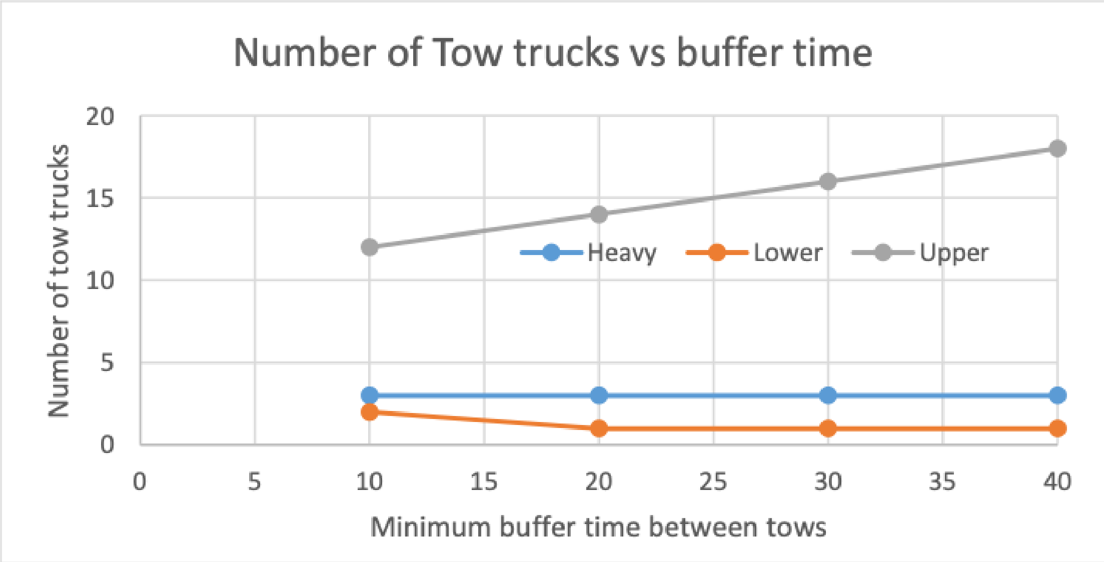


Figure 41: Impact of buffer time on number of tow trucks required

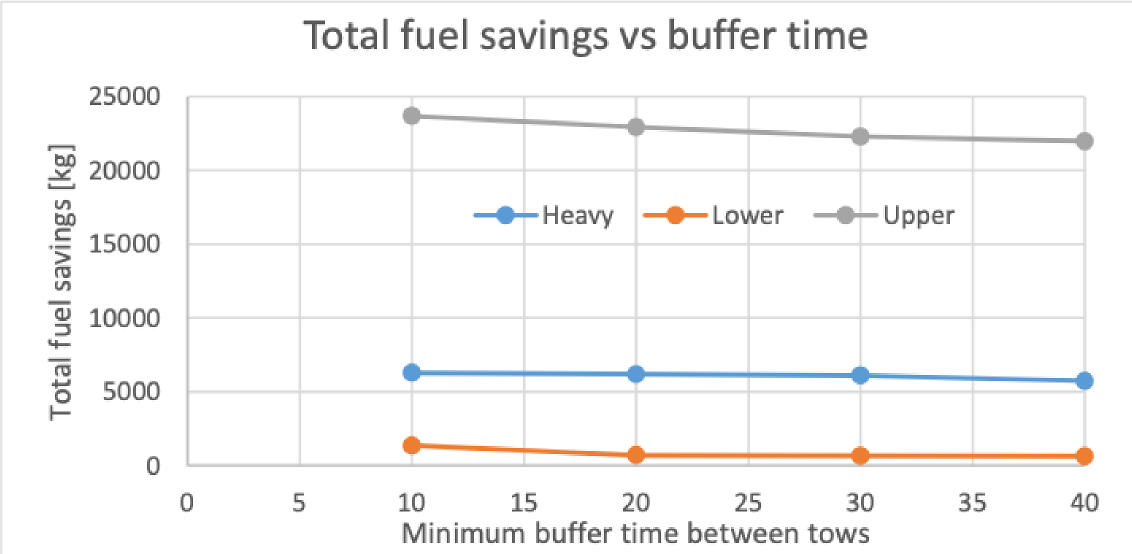


Figure 42: Impact of buffer time on total fuel savings

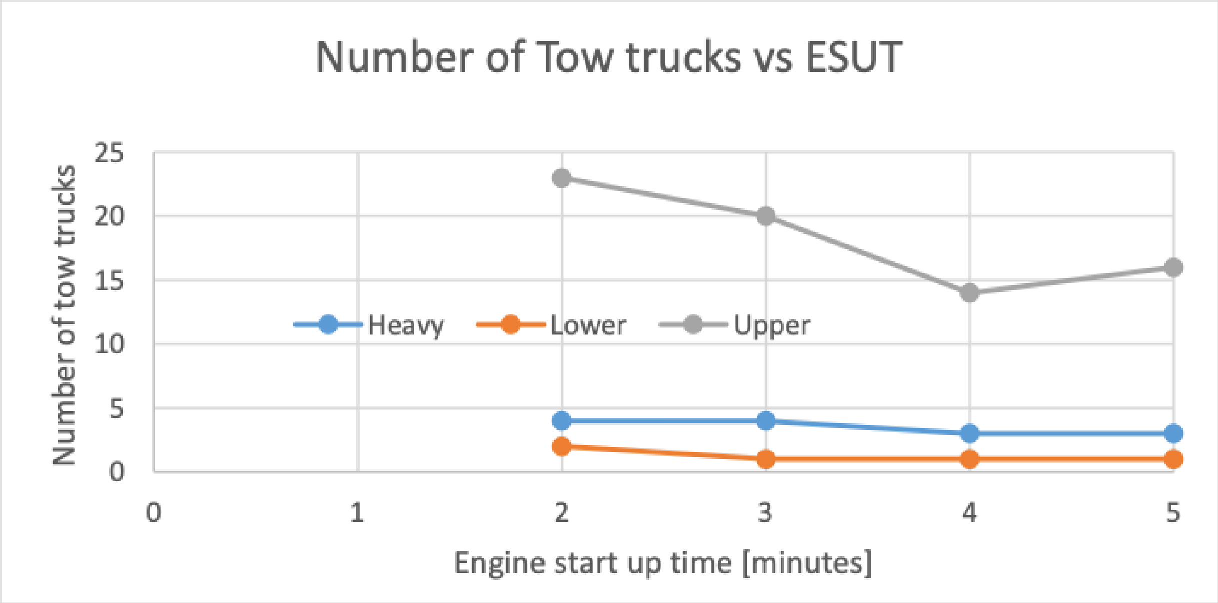


Figure 43: Impact of engine start up time number of tow trucks deployed

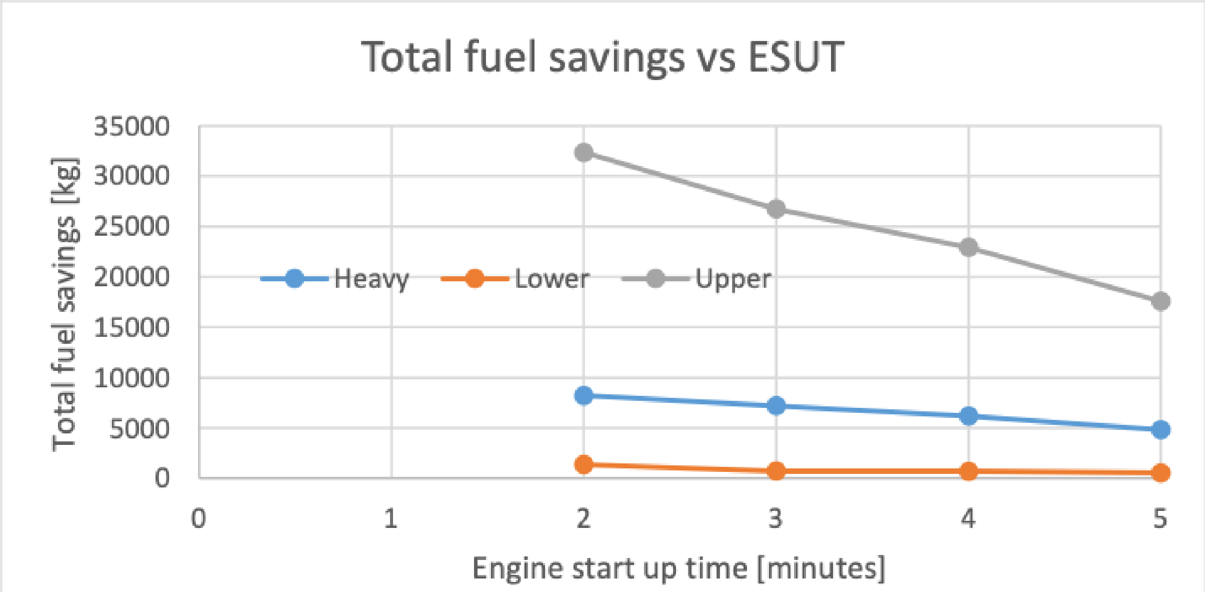


Figure 44: Impact of engine start up time number of tow trucks deployed

Methodology eTaxi

For the savings for installing an eTaxi system, the same values per airport were used for the impact per airport as for towing, however the values for high power APU usage where used. Additionally, a fuel penalty for the added weight was used, which was calculated based on the Breguet range equation.

Where R [km] is the range km], C [km] is the aircraft specific range parameter, WTO [kg] is the take-off weight and Wfuel [kg] is the fuel weight. Thus, we can deduce that the fuel required increases with respected to take of weight according to the following equation, and is thus independent of the actual take-off weight or fuel load.

These four representative aircraft were used to represent all aircraft in the flight schedule and the values are shown in table 43. The weight assumed for the ETS is a very rough estimation, as no flightworthy device is available yet and the total weight, including modifications to the APU and electrical system, is unknown.

Table 43: Representative aircraft range and ETS weight values

Aircraft	Range parameter C [km]	Added weight by eTaxi device[kg]
E190	21156	500
B738	19103	500
A320	23640	500
A350	32650	1000

Together with ICAO emissions data assuming climb thrust values for the cruise fuel consumption and the changes to taxi in and out fuel emissions and fuel consumption, a total impact of equipping an aircraft with a eTaxi device is calculated for each flight on each route, a few examples are shown in table 44. It should be noted that some KPI's (most notably NO_x) increases overall due to the added weight in cruise.

Table 44: Representative aircraft range and ETS weight values compared to normal taxi

Orig	Dest	AC	Range [km]	Cruise fuel [kg]	Taxi Out fuel [kg]	Taxi In fuel [kg]	ΔFuel [kg]	ΔCO_2 [kg]	ΔCO [g]	ΔHC [g]	ΔNO_X [kg]
AMS	MXP	B738	797	20	-108	-43	-130	-410	-1.8	0.15	0.36
AMS	MXP	A320	797	17	-98	-39	-120	-380	-2.7	0.03	0.29
AMS	LHR	B738	370	10	-108	-72	-170	-536	-4.6	-0.12	0.17
AMS	LHR	E190	370	9	-81	-54	-127	-401	-0.4	0.11	0.14
AMS	JFK	A350	5848	164	-287	-409	-532	-1682	92.1	-0.82	6.58

This data is then used in a which optimises the flow of aircraft equipped with ETS through an airlines day schedule and uses a fixed (marginal) costs for using ETS equipped aircraft per day. The model does not track the number of non-equipped aircraft nor the individual aircraft.

Table 45 shows the results for a very low marginal cost of 10 kg of fuel per equipped aircraft and illustrates the total savings if all aircraft were equipped. Note that while fuel and CO_2 emissions are always reduced, especially NOx emissions increase due to the added weight in flight. Assuming 80% average savings.

Table 46 shows if the installation of the system on an aircraft needs to be compensated by at least 1000 kg of fuel on a peak day and shows a significantly reduced number of aircraft equipped.

Table 45: Fuel and emission impact for a marginal fuel costs of 10 kg of fuel per installed eTaxi device

Code	Name	Type	Equipped AC	Fuel [tons]	CO_2 [tons]	CO [g]	HC [g]	NO_x [kg]
U2	Easyjet	A320	338	-192.7	-608.9	-2977	238.6	642.9
FR	Ryanair	B738	316	-136.9	-432.7	262	450.1	670.6
LH	Lufthansa	A320	166	-117.9	-372.7	-2543	39.0	289.5
VY	Vueling	A320	128	-84.8	-268.0	-1639	56.1	235.4
BA	British Airways	A320	90	-58.5	-184.8	-1199	26.9	150.2
AF	Air France	A320	85	-58.8	-185.9	-1192	30.4	154.9
EW	Eurowings	A320	108	-57.2	-180.8	-994	55.7	176.7
AZ	Alitalia	A320	64	-50.3	-158.9	-1215	-2.9	104.4
W6	Wizz Air	A320	111	-42.7	-135.1	122	168.9	255.3
IB	Iberia	A320	52	-39.2	-123.8	-767	23.6	106.1
Total			**1458**	**-839**	**-2651.7**	**-12143**	**1087**	**2786**
Yearly	**80% utilization**			**-245029**	**-774291**	**-3545828**	**317271**	**813523**

Table 46: Fuel and emission impact for a marginal fuel costs of 1000 kg of fuel per installed eTaxi device

Code	Name	Type	Equipped AC	Fuel [tons]	CO_2 [tons]	CO [g]	HC [g]	NO_x [kg]
U2	Easyjet	A320	36	-42.6	-134.6	-1144	-19.4	72.0
FR	Ryanair	B738	23	-29.4	-93.0	-652	0.1	49.3
LH	Lufthansa	A320	44	-55.3	-174.9	-1551	-34.3	84.8
VY	Vueling	A320	22	-30.1	-95.2	-835	-17.6	47.2
BA	British Airways	A320	15	-18.2	-57.4	-525	-14.2	24.8
AF	Air France	A320	14	-17.0	-53.9	-452	-7.2	29.3
EW	Eurowings	A320	6	-6.6	-20.9	-187	-4.3	9.9
AZ	Alitalia	A320	20	-25.4	-80.3	-708	-15.4	39.2
W6	Wizz Air	A320						
IB	Iberia	A320	12	-17.1	-54.0	-487	-12.1	24.6
Total			**192**	**-242**	**-764**	**-6542**	**-124**	**381**
Yearly	**80% utilization**			**-70600**	**-223097**	**-1910138**	**-36320**	**111268**

Finally, figure 45 and 46 show the impact of the weight of the ETS system and the marginal cost per installation for KLM 737 aircraft. As can be seen, both have a highly diminishing effect on the overall fuel and thus emissions savings. Figure 47 shows the impact on NO_x production is even more significant. The installation cost should be recoverable with a 500 kg fuel savings per day and the weight should be as low as possible.

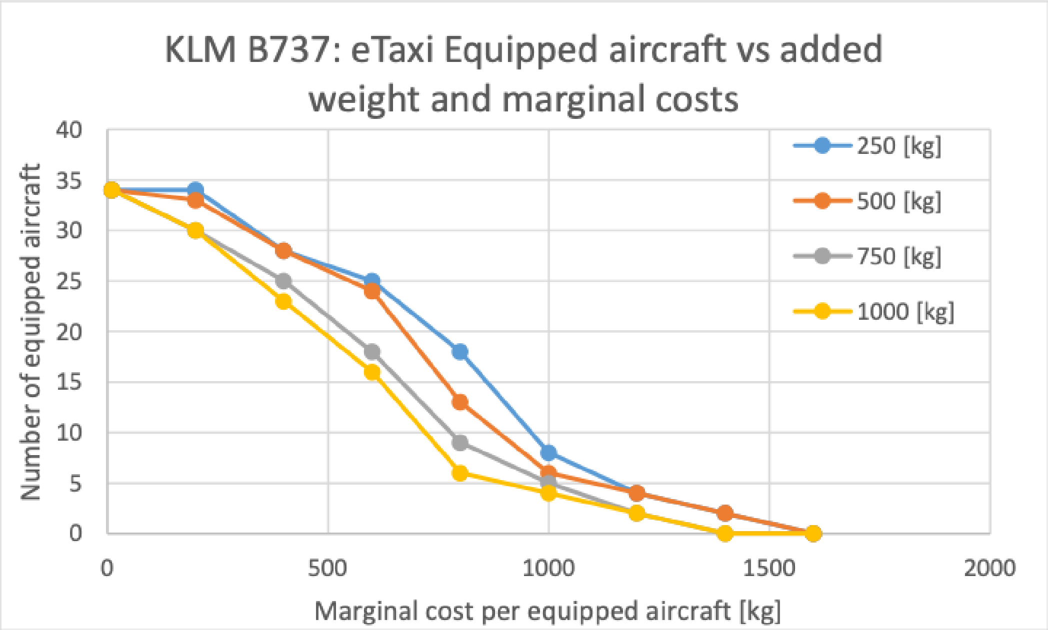


Figure 45: Impact of weight and marginal cost on the number of KLM 737 aircraft equipped

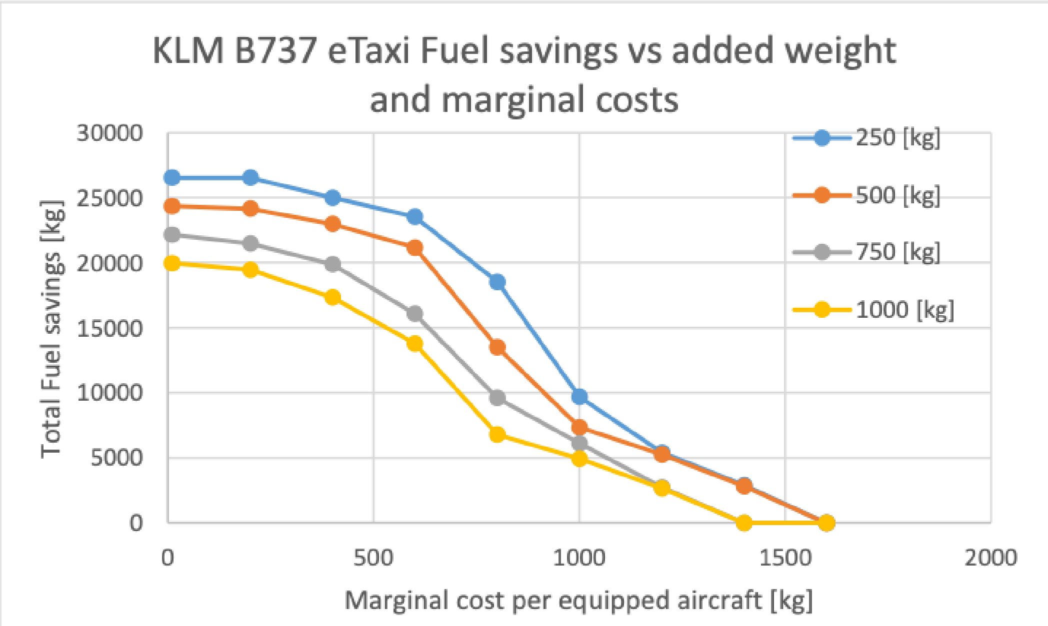


Figure 46: Impact of weight and marginal cost on fuel savings per peak day on KLM 737 aircraft

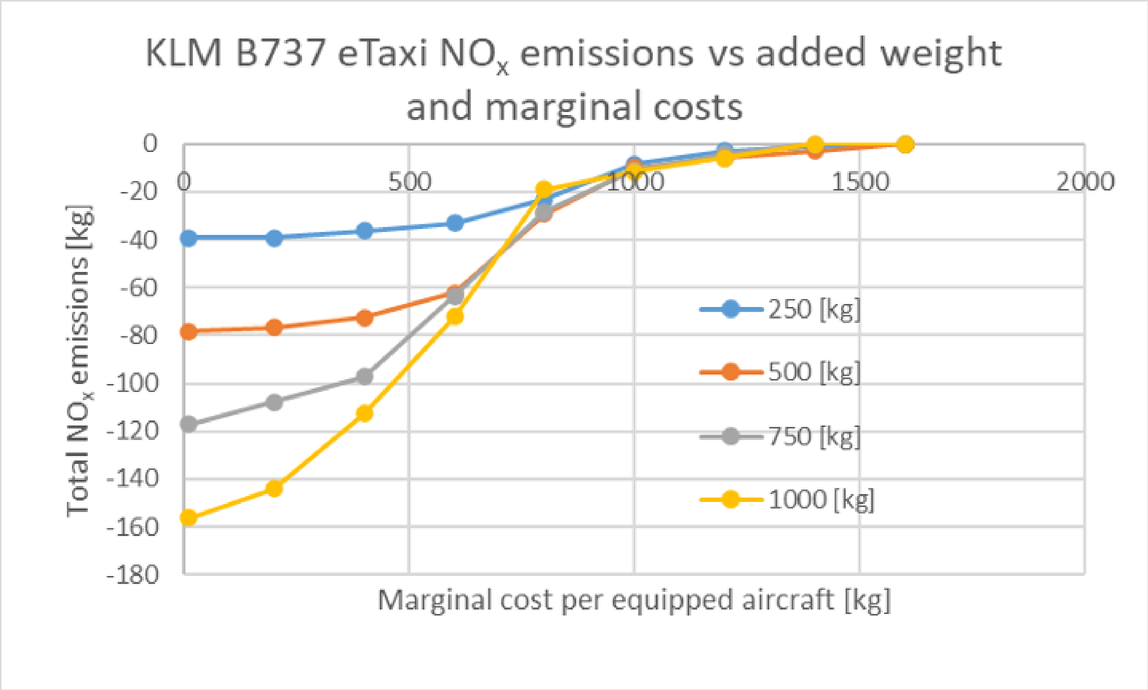


Figure 47: Impact of weight and marginal cost on NOx emissions per peak day on KLM 737 aircraft

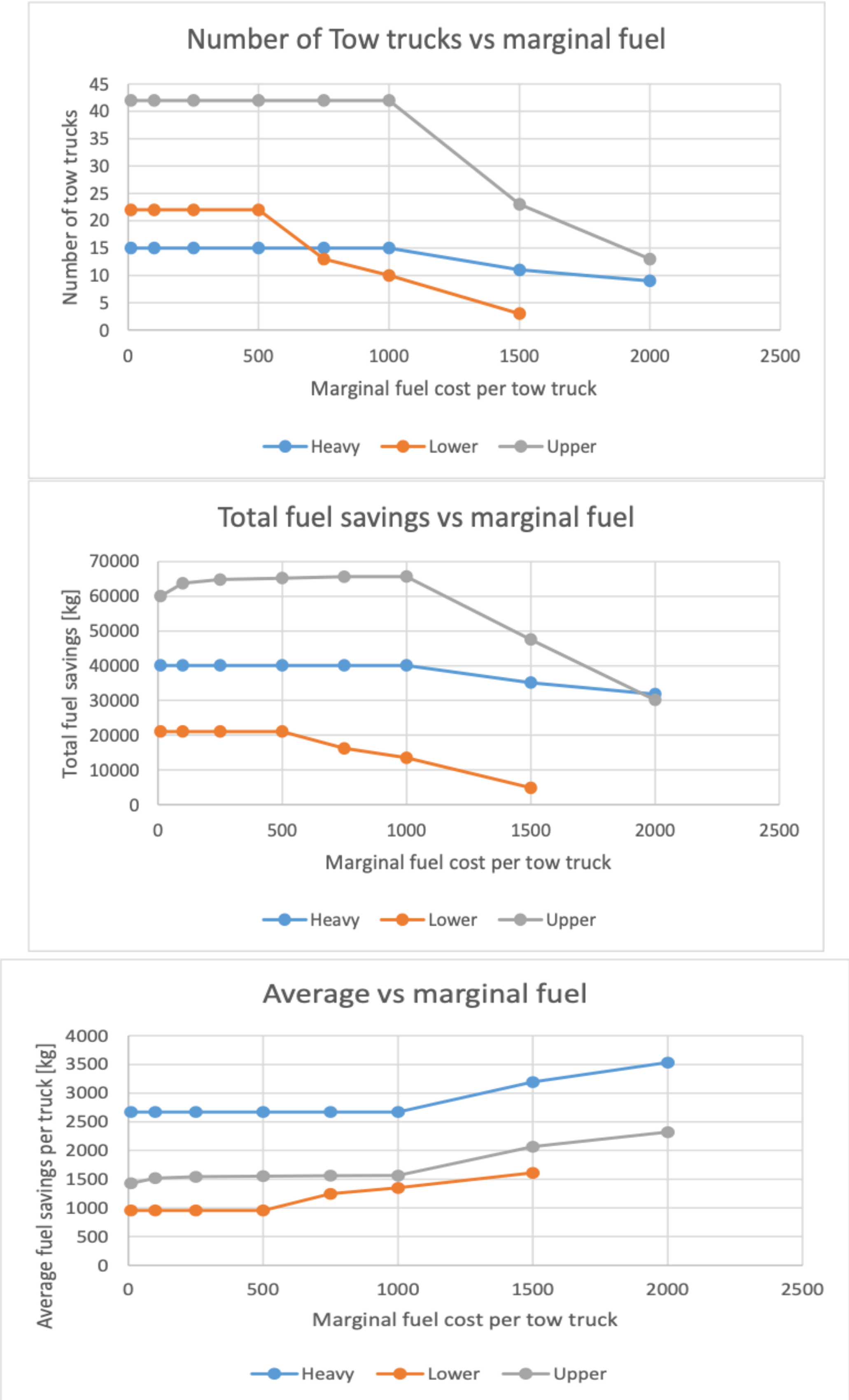


Figure 48. Marginal fuel values for AMS

Conclusions

Implementing operation towing at airports can significantly reduce fuel consumption and environmental impact of ground operations at airports. The upper bound of the total fuel that could potentially be saved at 2018 traffic levels is estimated at 1 billion kg within the European region, leading to 3.2 billion kg in reduction in CO_2 emissions.

A trade off must be made between the total savings by aircraft and the operation costs for tow trucks to find the optimum number that should be deployed at each airport, accepting that at peak periods not all aircraft can be towed, especially for arrivals.

Uncertainties that must be addressed and monitored are the buffer time needed for scheduling the tow trucks between towing aircraft and the time aircraft take to warm up and cool down the engines.

For towing, there is potential for fuel reduction, but this will always lead to an increase in NO_x emissions. The savings are however, very dependent on the weight of the system and the business case is affected by the costs of the system vs. the cost of fuel.

A.7 Electrification of ground vehicles and operations

The input data of the model consists of the number of ground vehicles at the airports of LIN and MXP, the vehicle category, fuel used, and average yearly distance covered. This file is automatically pre-processed using an ad-hoc code developed in Python.

1. The entire vehicle set is then divided into small, medium, and large, based on their model types.
2. 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.
3. For each size category, the number of vehicles and their yearly mileage 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.
4. 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 [52] [53]. Their range, capacity, and use, provide a value for the yearly electrical energy required to power the electric fleet.
5. The model uses literature results [54] [55] 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.
6. 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 using various sources of energy generation.
7. These percentages are used to calculate a series of possible reductions in global GHG emissions, due to the electrification of the ground operations fleet.
8. Using recent values for the global change in atmospheric CO_2 concentrations [56], a value for a resulting change in CO_2 ppm per ton of emissions is calculated.

9. The reduction to the yearly increase of radiative forcing (RF) alongside the concentration changes are used to calculate the change in average global temperature response in 20 and 100 years (ATR20 and ATR100, respectively), according to the equation proposed in the seminal work of Sausen and Schumann [27].
10. 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 electrical 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.
11. 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.

List of KPI Assessed

The following is a list of all the KPI being assessed in this OI, both climate related and non-climate related.

Table 47. List of KPIs used to assess the impact of this OI

Ground Fleet	Environmental	Financial
Number of vehicles in use	CO_2 emissions (K2.1)	Maintenance costs
Number of kilometres covered by the fleet	Non-CO_2 emissions (NO_X, CO, PM) (K2.2)	Purchase cost of electric vehicles
Fuel consumption	Average temperature response (ATR20, ATR100)	Fuel costs
Energy required to drive an equivalent electric fleet		Energy costs

Results

Assessment of climate KPIs

<u>Environmental results</u>

The main interest of this OI is to see how much less an electric airport ground operations fleet would impact the environment as opposed to the current fleet in use. For this, two metrics are used: Greenhouse gas emissions and impact on global temperature or Average Temperature Response (ATR). The model used can predict these values for an airport ground fleet of any size using reference data provided by the SEA airports. For consistency, results will be shown for an airport ground fleet of 1000 vehicles.

Our model predicts that a ground operations fleet of 100 vehicles would emit a yearly total of 4787 metric tons of GHG. The main contributor of the greenhouse gas composition is CO_2 at over 93% of the emissions. The remaining fraction of the emissions includes NO_X, SO_2, and CO.

To calculate the emissions of the theoretical electric fleet, the emissions of energy generation are used. The process to generate the required 3.29 million kWh will emit different amounts of greenhouse gases based on the method of energy generation. The following table shows the greenhouse gas emissions for different sources of electrical generation.

Table 48. GHG emitted per kWh for different sources of electric energy generation [55]

Electric Energy Generation Source	GHG emitted per kWh generated (kg)
Coal	1.199
Petroleum	0.869
Natural Gas	0.549
Average European Mix	**0.231**

The three sources generate energy by burning fuels and consequently they release the most emissions per kWh of energy generated. In Europe, energy is produced by a variety of sources, which include: petroleum products, natural gas, nuclear energy, fossil fuels and renewable sources. Renewable energy sources account for approximately 15.2% of the total energy generated.

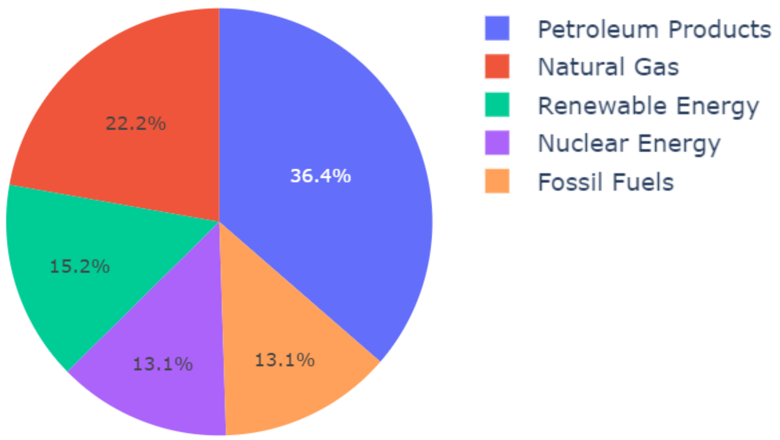


Figure 49: Graph showing the distribution of electrical energy generation sources present in the average European mix [55].

The following table shows the resulting prediction for yearly GHG emitted by generating the energy required to power an airport ground fleet of 1000 electric vehicles compared to the GHG released by a traditional fleet.

Table 49. Tons of GHG emitted per year for different sources of electric energy generation

Electric Energy Generation Source	GHG emitted in tons (1 year)
Traditional	4787
Coal Source	3944
Average European Mix	**759**

Results show 4787 tons of GHG emitted by a traditional fleet. The European mix of electrical energy sources would emit 759 tons of GHG. This is an 84.1% decrease in emissions.

To assess the global climate impact of the OI, we need to calculate the variation in global CO_2 concentration caused by the airport emissions. Since the impact scope is of a global scale, the global CO_2 emissions are used with the subsequent global change in CO2 concentration to obtain a change in concentration per ton of CO_2 emitted.

We need to calculate the variation in global CO2 concentration caused by the airport emissions.

- CO_2 emissions 2018 = 36.65 Billion tons [57]
- Atmospheric CO2 concentration increase after 2018 = 2.31 ppm [14]

We can see this yields an increase in CO_2 ppm of 6.3x10-11 per ton of CO_2 emitted. This simplification of calculating atmospheric concentration change does not reflect real CO_2 emission models or more sophisticated climate models. It does, however, provide a fast solution towards an estimation which deals with a comparatively small change in the concentration which, as shown later on, proves to be relatively inconsequential.

For the following calculations we will record two scenarios: Scenario 1 where the airport maintains the size 1000 fleet as it is and does not integrate the OI, and scenario 2 where the OI is completely integrated and all ground operation vehicles are replaced with electric equivalents.

Using the change in concentration calculation above, the change in CO_2 can be estimated for each of the two scenarios. In scenario 1, nothing changes, so we can assume that the global emissions will pursue their course and change in CO_2 ppm will remain unaltered. In scenario 2, 4028 tons of CO_2 are no longer being released into the atmosphere, translating into a proportional reduction in change of global CO_2 ppm. The calculation shows that the OI as applied to the fleet of 1000 vehicles would result in a 2.1x10-7 ppm reduction in the following year's CO_2 concentration increase.

For the following KPI (Radiative forcing and ATR) the equation used has been updated compared to the previous deliverable D2.3 to align the method to that adopted in the other OIs and introduce a more reliable comparability measure.

Radiative Forcing (RF) is the atmospheric change in energy flux caused by climate change, measured in Wm-2. As the CO_2 concentration increases, so does the RF. Sausen and Schumann [27] calculated the radiative forcing the following equation:

$$RF^*(t) = \frac{\ln(C(t)/C_0)}{\ln 2},$$

where C_0 is the concentration of CO_2 in the atmosphere at the start of the selected time period, and C(t) is the CO_2 concentration at the end of the time period.

We previously calculated the estimated CO_2 emissions of a size 1000 ground operations fleet 4787 tons. These emissions cause an increase in the global average CO_2 concentration of 2.5×10^{-7} ppm. Consequently, the normalised RF increases. In the formula used in D2.3, it was possible to measure the increase in radiative forcing and obtain a real-world value. However, since this new formula uses a normalised RF calculation, the value obtained has no real-world translation. The energy generation (e.g. with a typical EU mix) to power a fully electric fleet of 1000 vehicles produces 759 tons of CO_2 per year, which corresponds to a reduced global increase in CO_2 concentration of 4.8x10-8 ppm.

The last climate KPI being measured is the change in global temperature response that occurs if the OI is implemented, measured in K. It is calculated using Eq. (8) of Sausen and Schumann [27] with the radiative forcing calculation described above:

$$\Delta T(t) = \int_{t_0}^{t} G_T(t-t')\, RF^*(t')\, dt'$$

where t_0 is the starting year of the time period, t is the final year of the time period being calculated.

In this iteration of the OI, the 2001 IPCC Climate Change Report formula found in D2.3 has been updated with that used in the TransClim model [27] to consolidate results with other OIs. Results show that SEA Malpensa and Linate combined current fleets contribute an ATR of 1.0×10^{-9} Wm^{-2}. If the OI were implemented, the yearly global temperature contribution would drop to 1.6×10^{-10} K.

Table 50. Estimate of the yearly CO_2 emissions and concentration, Radiative Forcing, and Average Temperature Response for the current and electric replacement fleet

Fleet	Yearly CO_2 emissions (tons)	Yearly CO2 concentration contribution (ppm)	Yearly RF contribution (Wm^{-2})	Yearly temperature response contribution (K)
Current	4787	2.5×10^{-7}	3.3×10^{-9}	1.0×10^{-9}
Electric Replacement	759	4.8×10^{-8}	5.18×10^{-10}	1.6×10^{-10}

Results show that the highest contributing vehicle type, both in economic and environmental factors, are the large vehicles. This is due not only to their dominance in number, but also their fuel/energy requirements and frequency of use. Their replacement with electric equivalents will result in the most GHG saving as well as the largest increase in purchase cost, but also long-term fuel/energy cost savings.

Scaling to European Level

The long-term projection of the OI is for the climate impact of the electrification of ground operations to be calculated for all airports in the ECAC area. As previously stated, the number of ground operations vehicles for an airport is calculated from the yearly flight operation number in a linear model. Since for now the model is linear, it is possible to extrapolate the number of ground operation vehicles in the ECAC area from the aggregate sum of all ECAC flight operations. Once the number of vehicles is counted, the emissions and electric equivalent fleet, as well as the climate related and non-climate related KPIs can be calculated in the same method as for an individual airport.

For more information on the European impact of the ground scenario OI, please see document A11 Common Ground Scenario.

B. Assessment of non-climate KPIs

CBA

Though the focus of results has been the climate/related KPI, in order to move the OIs forward into fruition, non-climate KPIs have been calculated. These KPIs help the ClimOP project the introduction and future viability of the OI in operation.

The starting point of the financial KPI is a cost-benefit analysis covering the status of the electric vehicle and energy markets. The results of said cost benefit analysis can be summarised as such:

Table 51: Costs of fuel type units as of August 2021 [58]

Fuel Type	Unit	Cost per Unit (€)
Petrol	litre	1.57
Diesel	litre	1.48
Electric	kWh	0.04

Table 52: Average purchase and yearly maintenance costs for the different sizes of vehicles for each fuel type considering the typical average mileage of these vehicles at an airport [59] [60].

Vehicle size	Fuel type	Average purchase cost (k€)	Average annual maintenance cost (€/km)
small	petrol	19.2	0.043
medium	petrol	27.8	0.048
large	petrol	82.6	0.18

small	diesel	20.8	0.043
medium	diesel	28.0	0.048
large	diesel	235.0	0.18
small	electric	26.1	0.038
medium	electric	34.9	0.042
large	electric	354.3	0.29

These costs are then used to extrapolate the respective costs for airports of any given size. For the purpose of this calculation, we use an example ground operations fleet of 1000 vehicles to project the non-climate KPI estimates.

Table 53: Average purchase and yearly maintenance costs and savings for the different sizes of vehicles for each fuel type.

Estimated Purchase Cost (€)	Current Yearly Fuel Cost (€)	Estimated Yearly Energy Cost (€)	Current Yearly Maintenance Cost (€)
208.44M	3.66M	312.47K	255.02K
Estimated Yearly Maintenance Cost (€)	**Estimated Yearly Fuel to Energy Savings (€)**	**Estimated Yearly Maintenance Savings (€)**	
124.58K	3.35M	130.44K	

The main takeaway from these results is the large initial purchase cost and yearly maintenance savings. If APTs are willing to make the initial investment, in the long run the financial benefits will come from the much easier maintenance of electric vehicles, stemming from their lower amount of moving parts when compared to traditional fuel-powered vehicles.

C. Uncertainty estimate

Various uncertainties stem from modelling the airport, assembling an electric equivalent fleet and extrapolating the data for all European airports.

The first source of uncertainty comes from the classification of the vehicle into its size categories. Though it serves as a great benefit when it comes to scaling, simplifying the fleet into small, medium, or large is a generalisation which affects accuracy. As this is the first uncertainty, it is carried throughout the calculations.

The second source of uncertainty pertaining to the modelling of ground operations fleets is the amount of ground operations vehicles present at any given airport. The prediction of the fleet size stems from the number of yearly flight operations at the airport. For this, the two SEA airports have served as a basis for a linear model of fleet size estimates. Once the model was made, IATA provided the size and distribution of the ground operations fleet at Ibiza airport. The cross reference showed an error of +/-54.6%. As more airports share their data this error will be reduced as the model is adjusted to reflect the real distribution of vehicles to flight operations more accurately.

Electricity generation sources and emissions

Using an average EU mix of energy generation sources, the corresponding emissions are not those exactly reflected by the specific energy production which differs across countries and regions, and even for individual airports, which in some cases may have the capability of producing their own energy. In the case of the Milan airports, for example, SEA has its own infrastructure to produce energy.

CO_2 tons to ppm

We have taken the global CO_2 emissions and increase in ppm for 2018 as an indicator of how much the SEA CO_2 tons will increase the ppm, this uses the global values and is not necessarily indicative of how much the global CO_2 ppm is affected by releasing tons of CO_2 in Linate or Malpensa.

Cost of electric vehicles

The purchase cost of each electric vehicle size has been averaged using the costs of the electric equivalents for models found in each size category. This does not reflect the distribution of costs of vehicles within the same category and also the fact that for some of the largest vehicles an electric equivalent currently does not exist.

Energy cost

The calculation of the energy costs necessary to power the electric fleet, an average value of the cost of energy for businesses in northern Italy in the year 2018 was adopted. This is not necessarily the price an individual airport would pay, especially if the airport produces part or all its energy demand. In addition, the recent surge in energy price in recent years, and particularly since the beginning of the Ukraine crisis, indicates that this estimate may vary significantly depending on the circumstances, and the values computed in the present analysis should be therefore interpreted as an order-of-magnitude indication.

D. Comparability of the results with the other OIs

The vehicle data for the model is based on the year 2018. The ground operations SEA data encompasses all 365 days of 2018, from the 1st January to the 31st December. The model is based on 2018 data to avoid including the impact of the COVID-19 pandemic in the model. Flight numbers and operations are calculated as they were before the global pandemic drastically reduced the flight operations worldwide to anomalous lows. The temperature impact is measured after 20 years (ATR20) and after 100 years (ATR100).

The geographical scope of the model is based on is on the LIN and MXP airports which make up 3% of all flights in ECAC space. This number refers to the flights operated at these airports in the year 2018 (approximately 3.1×10^5) divided by the total number of flights in the ECAC area in 2018 (approximately 11 M). The number of ground vehicles at an airport are assumed to scale linearly with the number of flight operations at that airport. The proportionality constants are derived using LIN and MXP as reference. The fleet composition of all ECAC airports is extrapolated using this relation.

E. Applicability of the OI

The applicability of an OI has three aspects: Technical, organisational and regulatory. In the case of the electrification of ground operations, technical applicability references the technical advancements or changes that must take place in order for the OI to be installed and run in the airport environment. Many of the vehicles found at the SEA premises have electrical equivalents, the specification of which is sufficient to operate at the same rate as before. However, there are certain large specialised vehicles which do not have electric equivalents. Some of these have been identified to have alternative vehicles in the market that are hydrogen-powered. These alternatives have yet to be explored, though as time goes on the availability of electric equivalent vehicles increases and larger scale production of these becomes more readily available for European airports as a whole.

The organisational applicability of the electrification of ground operations consists in the electric vehicle network. Many changes to the airport have to be made to accommodate electric vehicles which come with characteristics which shape their use and the awareness of personnel in their surroundings. Electric vehicles have lower overall ranges than traditional fuel powered vehicles and so need to recharge more frequently. The recharging process takes longer in electric vehicles than refuelling a traditional vehicle. A recharging plan needs to be drawn so that all the necessary vehicles are operational and sufficiently powered throughout the day. This might involve a rotation of electric vehicles being employed at different times of day as a wave of vehicles recharges. This could result in the purchase of additional electric vehicles. Another issue with the recharging function is space. Electric vehicles (EVs) need to have allocated recharging spaces at stations where the energy socket is installed. There need to be sufficient recharging stations for the vehicles that need to recharge at the same time at any given point in the day.

<u>Safety Assessment</u>

The electrification of ground operations requires a large number of additional installations to support the operation of electric vehicles, both in terms of physical resources and personnel training. Electric vehicles, their characteristics, and the processes involved in operating them and their peripherals entail new sets of risks which have to be addressed.

Hazards were identified in 3 sectors. The vehicles and their components, the processes involving supporting infrastructure and hazards during daily operation.

The EVs themselves host different components which bring a new set of hazards, specifically to do with the batteries. The most common type of battery found in EVs is lithium-ion. Elevated self-discharge of lithium-ion batteries can cause their temperature to increase which has a chance to develop into a Thermal Runaway. This means that damage to the cell can lead to impurities penetrating it. A major electrical short can develop and a sizable current will flow between the positive and negative plates of the battery. There is a sudden rise in temperature and the energy stored in the battery is released within milliseconds. During thermal runaway, heat generated by a damaged cell can move to the next cell, causing instability in a chain reaction that can destroy the pack within a few seconds. For this reason, fire and explosion hazards are introduced with the use of EVs.

There are hazards found in the handling of EV peripherals, namely EV charging stations. The storage of electrical energy and the recharging of vehicles has a chance of causing electric shock with the potential to cause explosions or fires. Combustion can be due to silicon expansion within the battery from exposure to heat, as well as dendrite formation within, which could also damage the battery. Other hazards stem from the manual handling of heavy battery packs during replacement or disposal.

The main hazard encountered during the operation of EVs is pedestrian collision. Electric vehicles run very silently. This gives little warning of their presence to people in its surroundings, making the risk of an accident higher than for traditional vehicles. To mitigate this, personnel need to be made aware of the use of EV, and to take extra precautions when working in their vicinity, as well as when driving the EVs.

Table 54. Example classification of different events based on the frequency of occurrence.

Frequency	Class	Qualitative definition
< 1 / 1000000	1	Extremely improbable. Should virtually never occur in the lifetime of the considered system.
10 / 1000000	2	Extremely remote. Unlikely to occur when considering several systems of the same type, but nevertheless has to be considered as being possible.
50 / 1000000	3	Remote. Unlikely to occur during the total lifetime of the system but may occur several times when considering several systems of the same type.
100 / 1000000	4	Reasonably probable. May occur during the total operational lifetime of one system.
500 / 1000000	5	Frequent. May occur multiple times during the total operational lifetime of one system.

Table 55. Example classification of events based on severity

Severity	Class	Qualitative definition
Accident	A	Accident or significant incident with the potential for significant number of fatalities or serious injuries.
Major incident	B	Major event with potential for serious damages to the system and injuries
Significant incident	C	An incident indicating that an accident or a major incident might have occurred, if the risk has not been managed within safety margins.
No safety effect	D	An incident which has no safety significance
Not determined	E	Insufficient information available to determine the risk involved

Table 56. Example risk matrix which can be used to determine whether a system is within well-defined, tolerable risk levels (green) or organisational resources should be allocated to increase the safety.

Risk Matrix	**E**	**D**	**C**	**B**	**A**
1	Low	Low	Low	Medium	Medium
2	Low	Low	Medium	Medium	High
3	Low	Medium	Medium	High	High
4	Medium	Medium	High	High	High
5	Medium	High	High	High	High

To more safely work with EVs:

- Warn others about the current state of the vehicle being worked on.
- Only use insulated tools when carrying out repair or maintenance work on the vehicles.
- Be overprotective when it comes to safety clothing.
- Attend a safety training course to develop skills and knowledge.
- Define new procedures for the usage of new EVs.
- Use safety signs to assist in ensuring that correct procedures are being adhered to.
- Lock off and isolate before working on electric and hybrid vehicles.

Conclusions

We have observed that the relative impact on climate that the electrification of ground operations has is large (84.1%). The key hypothesis is that electrifying the ground operations fleet will have a long-term positive impact on climate is true as far as the predicted results show. The difference in GHG emissions between the burning of fuels in traditional diesel and petrol vehicles, and the GHG emissions produced from generating the required energy to power an electric equivalent fleet for the same intensity of operations is in fact quite large. This means that this lower amount of emissions will reduce the impact on the earth's temperature. However, is the difference big enough to warrant investment in the electrification of ground operations?

From a climate perspective, the relative decrease in emissions and temperature impact is the highest among all ground scenario OIs. However, when comparing this to the net share of emissions and temperature impact reduction, the electrification of ground operations is dwarfed by the results shown by the electric e-taxiing OI, which holds a share of 90% of savings. More detail on the comparisons between the OIs can be found in the ground scenario report A11. Perhaps airports will find efforts are better focused on the taxiing OI.

In terms of non-climate KPI, the electrification of ground operation shows good long-term promise. The biggest drawback is the initial cost of replacing the fleet. This could be a considerable deterrent for airports who are focused on short-term deadlines and quick-win financials. The applicability of the electrification of ground operation is not the simplest either, with large changes in infrastructure, personnel upskilling and training, operational rotations of vehicles and added hazards. However, the predictions show that in the long term this OI will prove beneficial for the climate as well as for airport finances.

A.8 Upgrade of the airport infrastructure according to energy efficient criteria

Airport buildings consume a significant amount of energy to maintain comfortable occupancy conditions, which require space heating and domestic hot water preparation, ventilation and air conditioning/cooling, power supply for lighting and other airport systems (e.g., elevator.). The improvements in the infrastructure according to energy-efficient criteria are expected to significantly reduce the energy consumption of airports, and hence their GHG emissions. Applying energy-efficiency measures to the airport infrastructure is immediately feasible and is effective over the long term. However, the initial investment is rather demanding, and the renovation works might cause problems for the operations, especially when they are carried out at terminals. This assessment clarifies the effectiveness of the OI in reducing airport impact on climate, the operational and economic impact on the key stakeholders, and how it is perceived by them.

Methodology

The assessment of this OI focuses on the analysis of the change in CO_2 emissions thanks to the application of a selection of energy-efficiency measures to the office buildings of European airports. The analysed energy-efficiency measures follow.

- Insulation of exterior walls.
- Optimization of windows.
- Introduction of LED lights.

For a comprehensive description of the applied method, we refer to D2.2 [10] and D2.3 [11]. Hereafter, we briefly summarise the key assumptions and the general strategy.

The assessment strategy entails five steps.

1. Identification of climate zones

Each EU airport is associated with one of the 4 most common climate zones by following the ASHRAE classification of geographical distribution of climate conditions [24]. To this end, the 2-metres temperature of the ECMWF reanalysis products, ERA5, is used to calculate the Heating Degree Days (HDD) and the Cooling Degree Days (CDD). HDD is a measure designed to quantify the demand for energy needed to heat a building, while CDD is the corresponding measure for cooling. They are defined as follows:

$$HDD = \sum_i max(0, T_{HDD} - T_i)$$

$$CDD = \sum_i max(0, T_i - T_{CDD})$$

Where T_i is the average value of temperature calculated per day of year over the time window 2015-2020, T_{HDD} is 18°C and T_{CDD} is 10°C, the two reference temperatures used for the climate zone classification of ASHRAE. We associate the location of each European airport [61] [62] with the HDD and CDD values of the closest grid point of ERA5 grid. Then, we follow the ASHRAE standards for the classification in climate zones [61]. In this way, all airports in Europe are directly linked to the climate zone of their geographical location.

2. Energy simulation of a conceptual office building

For each climate zone, we simulate the energy consumption of a conceptual office building by using EnergyPlus, the open-source software developed by the US Department of Energy. The simulated building is a medium-sized office building, with three floors, covering a total area of about 5000 m^2, and with a window-to-wall ratio of 33%. The simulation is repeated for all the considered energy efficiency measures.

3. Generalisation of the energy consumption at airport level

We scale the results to the total energy consumption for each airport with a proxy calculated as a logarithmic function of the number of aircraft movements. We consider 2019 as the reference year for the "business as usual" to avoid including the effect of COVID-19 pandemic. The scaling procedure has been validated with the data of the Energy Audit 2019 of Malpensa and Linate Airports provided by the ClimOP partner SEA [11].

4. CO_2 emission calculation

The CO_2 emission resulting from the energy consumption is estimated by using the procedure and conversion factors reported in D2.3 [11].

5. ATR calculation

The procedure is repeated for future climate conditions. The EnergyPlus model includes a module for future-climate simulations, that is based on climate conditions representative of 2050 for four emission scenarios as defined in the Special Report on Emissions Scenarios (SRES) report [63]. The corresponding Shared Socioeconomic Pathways (SSPs) for the Coupled-Model Intercomparison Project 6 (CMIP6) are considered, namely SSP1-2.6 and SSP2-4.5 corresponding to SRES B1 and B2, and A1 and A2 respectively.

It is worth describing in detail how step 1 of the procedure is performed for future climate conditions. The results of CMIP6 for five models are considered, namely HadGEM3-GC31-LL, EC-Earth3-CC, GFDL-ESM4, IPSL-CM6A-LR and MPI-ESM1-2-LR. The data are interpolated onto the ERA5 horizontal grid using the nearest neighbours method. HDD and CDD are calculated in the time window 2015-2020, for present-day climate, and 2048-2052, for future climate. The model-mean difference between the two is, then, added to the ERA5 values of HDD and CDD, and the climate zone classification is applied.

By repeating the procedure for 2050, we obtain two values of CO_2 emissions, one for 2019 and one for 2050. Finally, we calculate the Average Temperature Response (ATR) over 20 and 100 years by using the formulation introduced in Sausen and Schumann (2000) [27]. To this end, we linearly interpolate in time the values of CO_2 emissions to obtain a yearly value that takes into consideration the variation in energy consumption due to climate change. These values are used as input for ATR calculations.

The OI assessment will include the following KPIs:

- Environmental KPIs: ATR20, ATR100, annual electricity consumption per unit of volume, annual thermal energy consumption per unit of volume;
- Operational KPIs: tons of CO_2 emitted annually, CO_2 emitted annually in PPM;
- Economic KPIs: initial investment, annual economic savings thanks to the reduction of energy consumption, time to return of investment;
- Qualitative KPIs: social acceptance, market acceptance, political acceptance.

Results

A. Assessment of climate KPIs

For a detailed discussion of the results of the conceptual office building, we refer to D2.3 [11]. Here, we discuss the overall climate assessment of this OI in light of the introduced improvements. In particular, the analysis has been refined by associating each airport with its corresponding climate zone and by implementing the formulation of Sausen and Schumann (2000) [27] for ATR calculation.

In D2.3 [11], each Country in Europe was associated with the percentages of the area covered by the 4 climate zones. The percentage was then used to scale the results of the conceptual building to Country level. However, this approach implies that the aircraft movements are equally distributed throughout the Country, which is not the case in reality. This assumption is not necessary because of the direct association of airport location with the corresponding climate zones. Figure 50 shows the total energy saving in TOE and the corresponding CO_2 saving for each Country separately. The results show very notably the effect of airports located in northern Europe, where the energy efficiency measures are more effective (see D2.3 [11]), and with a high number of aircraft movements. As a result, the UK is the Country with the highest climate potential.

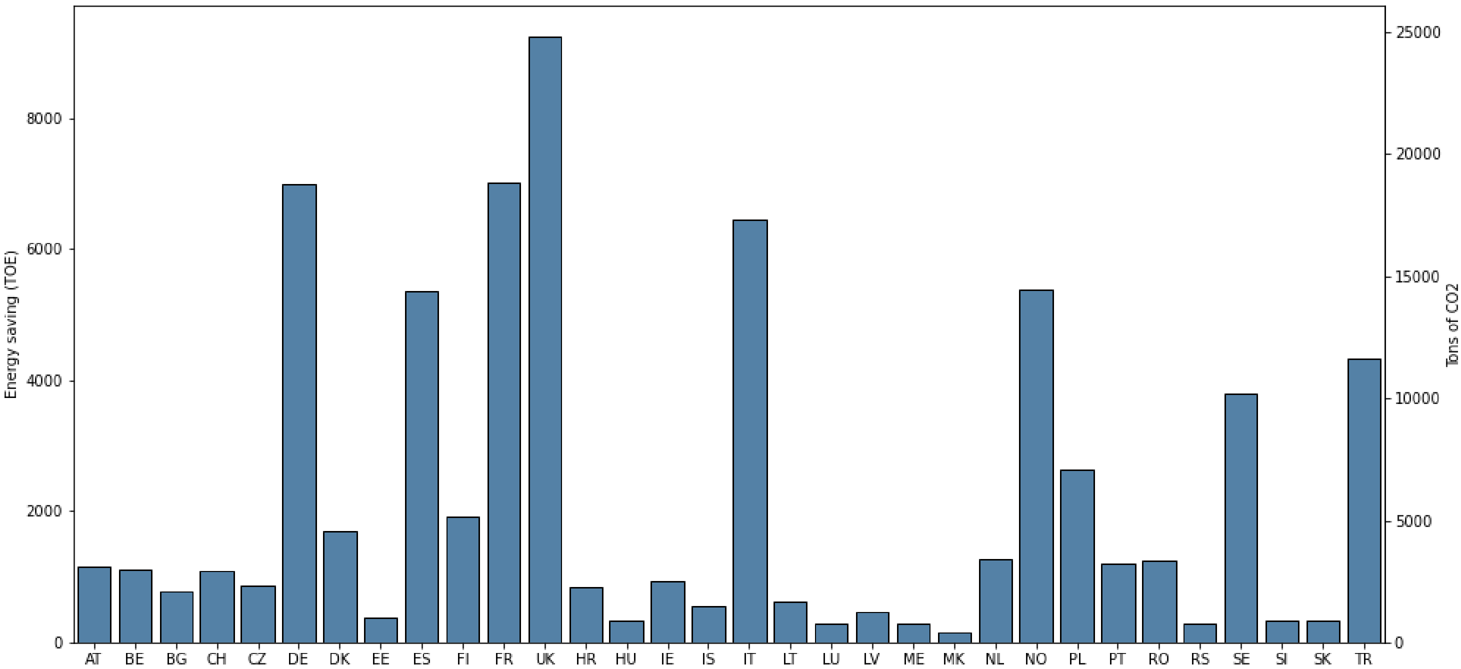


Figure 50. Total energy saving due to all the energy-efficiency measures in TOE and the corresponding CO_2 saving by Country.

The results for the future depend on how the climate will change. Figure 51 displays the climate zone at the location of each analysed airport in 2019 and 2050 for the two considered SSP scenarios. A general shift towards warmer conditions is notable in most of the continent, especially for SSP2-4.5. In particular, the Mediterranean region shows a clear transition from mixed to warm, and the Scandinavian region displays even larger temperature increase, with some airport locations shifting from cold to mixed climate.

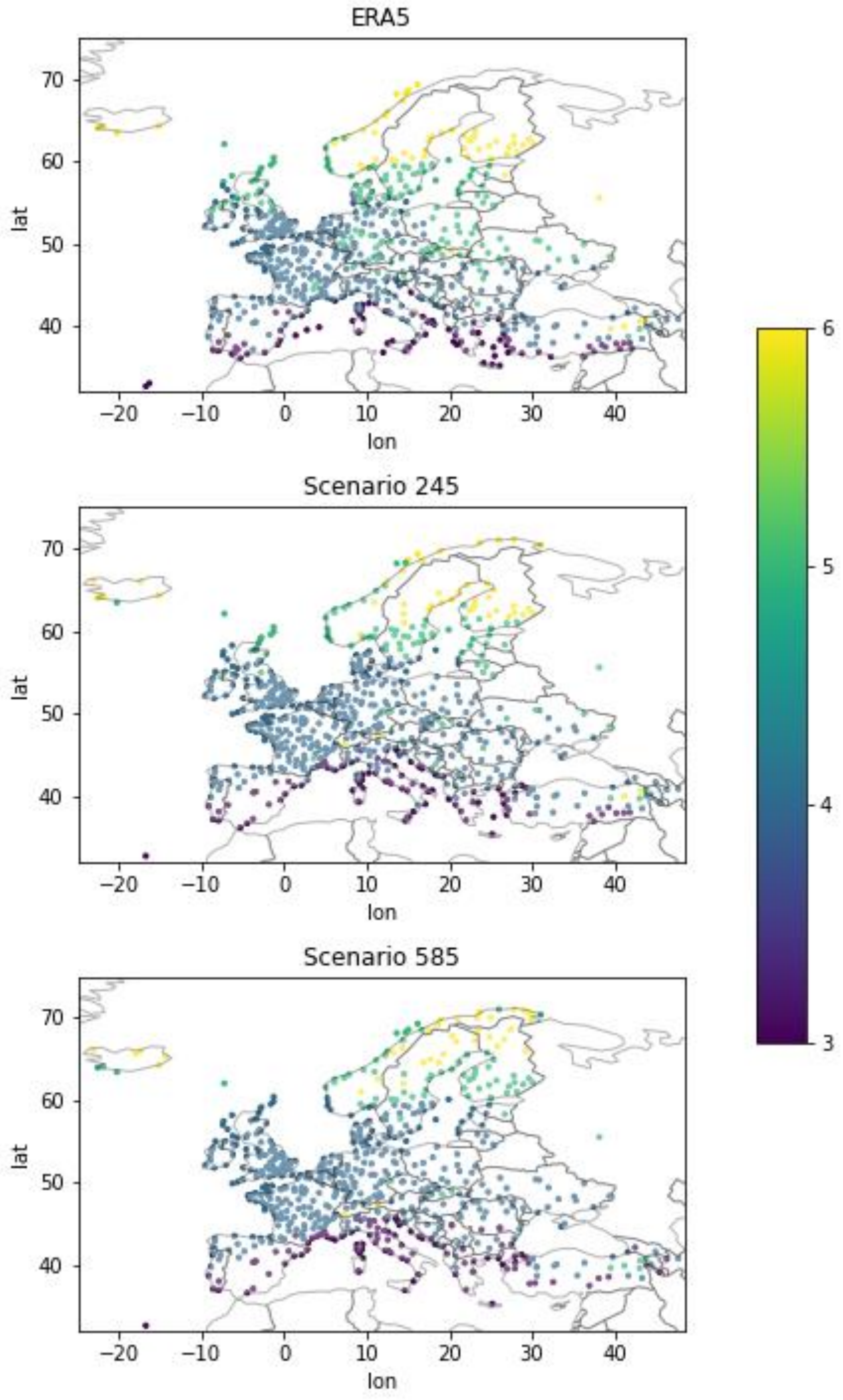


Figure 51. Climate zone corresponding to the location of each analysed airport. The markers indicate the airports and are coloured according to ASHRAE climate zones. The top panel shows the present-day condition, the middle panel the conditions in 2050 for the scenario SSP2-4.5, and the bottom panel for scenario SSP5-8.5.

We can now calculate ATR20 and ATR100 for business as usual and for the case including the OI, and compare the results. Table 57 summarises our findings for the different future climate scenarios. The present OI is consistently effective despite the considered socio-economic scenario.

Table 57. ATR20 and ATR100 values for the four climate scenarios analysed for business as usual (BAU) and after the implementation of the OI (OI). The difference between the two as a percentage of the business as usual value is also provided.

		A1	A2	B1	B2
ATR20	BAU (10^{-6} K)	1.67	1.66	1.66	1.67
	OI (10^{-6} K)	1.30	1.31	1.30	1.31
	Δ (%)	21.81	21.57	21.68	21.67
ATR100	BAU (10^{-6} K)	8.11	8.05	8.06	8.12
	OI (10^{-6} K)	6.26	6.32	6.28	6.33
	Δ (%)	22.78	21.57	21.68	21.67

B. Assessment of non-climate KPIs

In a second step, we aim to assess the impact on the key stakeholders through selected non-climate KPIs. Such KPIs tackle the economic impact, and the social and political acceptance.

To assess the economic impact, a Cost-Benefit Analysis (CBA) has been performed. We first focus on the analysis for the conceptual office building, and then scale the results using the generalisation method defined before. This procedure is based on the hypothesis that the initial investment for the implementation of the considered energy efficiency measures scales logarithmically with the number of flight movements, as for the energy consumption. This hypothesis is problematic to demonstrate as very specific data, rarely available, are necessary. For the time being, we consider the hypothesis to reach a first order evaluation.

The unitary costs for the implementation of the energy efficiency measures are collected in Table 58. The characteristics of the conceptual office building are then used to calculate the overall initial investment for one office building. The conceptual office building has a wall and roof area of 880.27 sm, a window area of 59.68 sm, and a ceiling area of 1796,28 sm. The wall and roof area is multiplied by the unitary cost for the insulation of exterior walls, the window area by the cost for optimization of windows, and the ceiling area by the cost for the introduction of LED lights. As a result, the cost to upgrade the conceptual office building is around 70,000 €.

Table 58. Unitary costs necessary for the implementation of the energy efficiency measures under consideration.

Energy efficiency measure	Unitary cost	Source
Insulation of exterior walls	63.50 €/sm	https://doi.org/10.1016/j.energy.2015.07.107
Optimization of windows	75 €/sm	https://doi.org/10.1016/j.enbuild.2012.02.022
Introduction of LED lights	0.63 $/sf	https://doi.org/10.1016/j.enbuild.2012.02.022

The benefit of implementing the energy efficiency measures is the reduction of the expenses for energy consumption. The savings are estimated based on the hypothesis that only electric energy is used, in line with the results for climate KPIs. For a detailed discussion on this hypothesis, we refer to D2.3 [11]. The costs of electric energy in 2019 [64] are considered such that we avoid including the effect of the COVID pandemic. However, the Ukrainian crisis highlighted how erratic the price of energy can be, and consequently that this is another major assumption of the present CBA.

The economic savings are estimated on the basis of the unitary cost of energy and of the difference of energy demand between the business as usual and upgraded cases. The unitary cost of energy depends on the Country and on the total energy consumption of the airport. For the total energy consumption at airport level, we multiply the energy consumption for the office building by a factor 10, in line with the comparison with SEA Milan data that highlighted that the office buildings account for around 10% of the airport energy consumption.

Table 59 includes the results of the CBA for a conceptual office building. In this case, we use the average energy cost over the EU27 countries, in the energy consumption range from 20 to 70 GWh. The economic saving is used for calculating the years to Return Of Investment (ROI). The investment is recouped in 7 to 16 years, depending on the climate zone where the airport is located.

Table 59. Results of the CBA for the conceptual office building, including the percentage of energy saving, the annual economic saving and the years to return of investment.

Climate Zone	Energy saving (%)	Economic saving (€/year)	Years to ROI (years)
3 – warm	21.07	5111.64	15
4 – mixed	18.63	4551.78	16
5 – cool	26.99	7284.20	10
6 – cold	30.95	10496.78	7

The result for one conceptual office building is then scaled by using the previously defined logarithmic function. We analyse the case of Malpensa and Linate airport as a reference. The initial investment is about 5 M€, and it is recouped after around 50 years. It is worth stressing that this CBA has its own limitations. It is based on rather speculative hypotheses that would need deeper analysis, for instance through specific case studies. However, we believe that the results can give an idea of the economic advantages of such an OI.

Besides the economic assessment, we investigate the social acceptance of this OI thanks to the ClimOP survey. The respondents were asked about their interest in the climate neutrality of an airport they travel to and from. Results show that 58.6% of respondents are absolutely in favour (N=127) and in favour (N=110), while 31.6% are neutral (N=128). Therefore, passengers are slightly in favour of travelling from a climate neutral airport. The slight preference may depend on the low awareness of what climate neutral airports are. Furthermore, discussions carried out during the AB meeting and an extra workshop with 11 European airports participating highlighted that the market acceptance of this OI is relatively high, despite the large initial investment. In fact, virtuous examples, like Amsterdam Schiphol, have already implemented all the suggested energy-efficiency measures. The OI is also politically well received, as some late policies and regulations concerning energy efficiency aspects suggest (e.g. 2. ICAO's Policies on Charges for Airports and Air Navigation Services (Doc 9082)).

C. Uncertainties estimate

Our calculation entails a wide range of uncertainties. The key sources of uncertainties are herein listed and linked to the different steps of the used methodology.

<u>Conceptual building modelling (Step 2-3):</u>

- *Utilisation of the conceptual office building: 20%*
  The same conceptual office building is used to assess the energy demand on any airport office building throughout Europe. The results are then scaled by using a logarithmic function of the number of flight movements. This simplification is necessary to reduce the complexity and generalise the results. We base the estimate of the corresponding uncertainty on the comparison between our results and the data of the Energy Audit 2019 of Malpensa and Linate Airports provided by the ClimOP partner SEA. In particular, we use as a benchmark the total electric energy consumption of the office buildings of Linate Airport. The uncertainty is about 20% of the estimated energy demand for all the airport office buildings.
- *Application of standard energy efficiency measures throughout Europe: 5%*
  The energy efficiency measures depend on the regulations in each Country. Therefore, considering the same energy-efficiency measures throughout Europe is another simplification. To estimate the uncertainties related to this assumption, we use as a benchmark the data provided by SEA coming from a preliminary analysis performed internally to explore the potential of energy efficiency measures for their airports. Based on the comparison with our results, we conclude that the uncertainty is about 5% of the energy savings by all the considered energy-efficiency measures.

Generalisation method (Step 3):

- *Energy demand dependence on the number of employees: 30%*
  The energy consumption of the conceptual building is scaled by using a proxy calculated for each airport as a logarithmic function of the number of aircraft movements. Such a proxy is estimated as the result of a logarithmic fit of the number of employees as a function of the number of aircraft movements for a tens of airports in Europe9. To estimate the relation to this assumption, we use the data of the Energy Audit 2019 of Malpensa and Linate Airports provided by SEA. Based on the comparison of our results with the total energy demand of Linate and Malpensa airports, we estimate an uncertainty of around 30%
- *Logarithmic fit error: 40%*
  The logarithmic fit itself has an error. We calculate the error of the fit as the absolute error. The uncertainty is around 40%. It is worth mentioning that this error does not take into account the potential error on the fitted data.

Emission modelling (Step 4):

- *CO_2 emission dependence on energy sources: 5%*
  The presented results are obtained considering the hypothesis that only electrical energy is used. However, airports commonly use a combination of energy sources. In D2.3 [11], we estimated the variability of our results due to different energy scenarios, where by energy scenarios we indicate different combinations of electric and thermal energy to satisfy the total energy demand. Such variability is considered as an estimate of the uncertainty related to the hypothesis on the energy source and amounts to about 5% of the total CO_2 saving.
- *Factors to convert energy consumption into CO_2 emission: 10%*
  The energy consumption is converted into CO_2 emission by using the conversion factors reported in Table 44. However, in literature, different values can be found. Through a literature review, we estimated an uncertainty of about 10%.

Climate modelling (Step 5):

- *Conversion of emissions to ATR: negligible*
  The calculation of ATR20 and ATR100 entails a numerical error due to the calculation of the integral. However, the numerical error is considered negligible as compared to the other uncertainties.
- *Future climate conditions: 1%*
  The effect of the present OI depends on how the climate will change as a result of the socio-economic development of our society. Four different assumptions have been considered, corresponding to the climate scenarios. The variability between those is limited, resulting in an uncertainty of less than 1% for both ATR20 and ATR100.

[9] Malpensa Milan Airport (Italy), Schiphol Amsterdam Airport (The Netherlands), Stansted London Airport (U.K), Frankfurt International Airport (Germany), Charles De Gaulle Paris Airport (France), Barcelona Airport (Spain), Athens Airport (Greece), Dublin Airport (Ireland), Geneva Airport (Switzerland), Marseille Airport (France), and an ideal small airport with 1000 aircraft movements a year and 100 employees.

D. Applicability of the OI

This OI does not present any applicability-related issues. It is immediately feasible and is effective over the long term. However, implementation of energy efficiency measures to the terminals might cause problems to the operations. It is worth stressing that the initial investment is rather conspicuous. Despite the economic benefits highlighted in our CBA, it might be necessary to analyse the economic applicability in view of potential policies.

Conclusions

This assessment aims to evaluate the potential for climate mitigation of upgrading the airport infrastructure according to energy efficiency criteria. In particular, the analysis focuses on office buildings and the application of a specific set of energy efficiency measures, including the insulation of exterior walls, the improvement of windows and the utilisation of LED lights. The study quantifies the reduction in ATR20 and ATR100 with respect to business as usual. Almost independently of future climate conditions, the reduction in ATR20 and ATR100 is around 20%, corresponding to values of the order of 10 nK.

Besides the climate assessment, the present OI is analysed from an economic point of view. To this end, we performed a CBA that analyses the time to ROI considering the savings thanks to the reduced energy consumption. The CBA clarifies that, although the initial investment is rather conspicuous, it is recouped in about 50 years for an airport such as Malpensa. Moreover, the ClimOP survey showed that the OI is well received by passengers (see Appendix C). The discussion with key stakeholders in the consortium, advisory board and beyond demonstrated that there are no operational or regulatory barriers for the implementation of this OI.

A.9 Ground-operation scenario

The present scenario combines the three OIs of ClimOP which are related with ground operations, equipment, and airport infrastructure, namely:

- Sustainable taxiing,
- Electrification of ground equipment and infrastructure,
- Upgrade of the airport infrastructure according to energy efficiency criteria

The goal of this scenario is to investigate the cumulative reduction of GHG emissions that can be achieved where all three OIs are deployed in an airport, and their integrated impact in terms of climate-change mitigation. The high-level purpose of this exercise is to provide a harmonised view of the extent to which an individual airport contributes to the anthropogenic effect on climate and thus support the collective effort of the Airport Operators in their path towards Net Zero by 2050. At a research level, the aim of this scenario is to describe a methodology for comparing the impacts on climate of different operational concepts, using the ground OIs as a case study.

Methodology

The basic hypothesis underlying the ground scenario is that the three OIs can be implemented independently, and therefore the total impact is calculated by adding the contribution of each individual OI. While this is a reasonable assumption that helps simplify the calculations, the modelling methodologies adopted in the three OIs differ substantially because of the very different aspects that are under investigation. As explained in the previous sections A.6–A.8, the impact of taxiing operations strongly depends on the airport layout, size, traffic, and adopted strategy. Quite different is the case of airport infrastructure, whose characteristics and available options to make it more energy-efficient vary in different geographical regions and on the detailed properties of the individual building to be upgraded. By contrast, ground support equipment and operations are relatively similar across airports although there might be differences in the size and composition of the ground fleet between airports that are seasonal or active the whole year. To level off the differences and consistently compare the impact of the three OIs on climate, it was therefore necessary to harmonise the modelling methodologies as described in the following.

The approach chosen to integrate these OIs was to focus on two case studies:

- A “high-resolution” analysis of the ground operations and infrastructure of MXP airport.
- A “low-resolution” analysis of the cumulative impact of all airports at the ECAC level, which is a parametric generalisation of the results of case study (a).

The reference year for both case studies is 2018.

<u>MXP Case study</u>

This case study builds on the detailed data shared within the ClimOP consortium by the SEA Milan partners. In particular, the modelling of taxiing operation is based on the taxi-in and taxi-out times that are recorded for a representative selection of narrow-body and wide-body aircraft types (cf. Sect. A.6) on a peak day. The preparation times in which the aircraft engines have to be active are assumed to be, respectively, four minutes for warming up before the take off and three minutes for cooling after the landing. The potential fuel reduction is calculated by considering the difference between the measured taxiing times and these engine-preparation times and multiplying the result for the average fuel consumption rate for the engine in idle (cf. Sect. A.6 for details). In this case study, it is assumed that the sustainable taxiing is achieved through electric towing, and the corresponding energy demand to power a fleet of electric tow trucks is calculated accordingly. It is assumed that approximately 80% of the values of fuel consumption and energy demand (and corresponding GHG emissions) are representative of an average day. These are subsequently multiplied by 365 to extrapolate the results to the entire reference year 2018.

The analysis of the potential emission cuts from the electrification of the fleet for ground support operations and from the upgrade of the airport office buildings is modelled as described in Sect. A.7 and A.8, respectively. Because SEA records the actual ground fleet composition and average daily mileage of each vehicle, and the energy consumption of different areas of the Malpensa Airport, this data can be used to benchmark the results of the models in terms of fuel and energy consumption in the business-as-usual for both operational improvements. The amount of emissions of different

GHG are calculated through the conversion factors for different pollutants available in the literature [25][26] 10, as described in Sect. A.7.

European Case study

The estimate of the cumulative impact of all airports at the European level requires a method to scale up the results obtained for the MXP. The adopted approach is the same as described in Sect. A.7 and A.8, respectively, for the electrification of the GSE and vehicles and the upgrade of the airport infrastructure. In particular, the number of flight operations is used as a proxy for the size of the airport and thus for its consumption of fuel and energy and GHG emissions. In the case of the ground fleet, the relationship between the number of yearly flight operations and that of ground vehicles is assumed to be linear. The energy consumption of office buildings is assumed to scale logarithmically with number of yearly flight operations (cf. Section A.8). The limitations of this approach are summarised in Section A.8.C. The same approach cannot be used to estimate the overall impact of taxiing operations, because different airports have very different taxiing times. To overcome this problem, an estimate of the total emissions from taxiing is calculated by considering (i) a set of the 10 busiest airports in Europe, (ii) the average taxiing times at these airports11, (iii) an A320 as a representative aircraft type to calculate the average fuel consumption.

2. Results

The list of KPIs and the results obtained for both case studies with the comparison of the different OIs are shown in Table 45. The cumulative results of the ground scenario are in Table 60. One of the outcomes of the models is that GSE and operations and the energy consumption for heating, cooling, and illuminating the office buildings produce about the same order of magnitude of CO_2 emissions. Cumulatively, these account for about 11% of all airport emissions (excluding those produced by passengers and cargo travelling to and from the airport, which are ignored in this analysis), whereas the largest share originates during taxiing. In this operation, more than 20 million litres of fuel are annually burnt in a mid-size airport such as MXP, which corresponds to approximately 60 thousand tons of CO_2 released per year in the business-as-usual scenario. Cumulatively, the CO_2 emissions from all ground operations, equipment and office infrastructure reach approximately 68 thousand tons per year. In terms of contribution to global warming, these emissions correspond to about 0.3 μK in 20 years and 3 μK in 100 years. The overall effect at a continental level is almost two orders of magnitude larger, with an expected contribution to global warming estimated at about 20μK in 20 years and 216μK in 100 years.

[10] In Environmental Assessment studies, a factor of 0.8 is commonly applied to the total PM_{10} amount to estimate the $PM_{2.5}$ concentration (M. Grampella, *priv. comm.*).
[11] Average taxiing time at the main EU airports are available on Eurocontrol's website. Those referenced in this context can be found at https://www.eurocontrol.int/publication/taxi-times-summer-2018 and https://www.eurocontrol.int/publication/taxi-times-winter-2018-2019.

Table 60. Summary of the results of the Ground scenario. The impact of each of the three ground-related OIs is evaluated against a set of KPIs for the detailed MXP and the generalised ECAC case studies, respectively.

KPI	MXP case study		ECAC case study		
	BAU	With OIs	BAU	With OIs	
CO_2 Emissions (tons/year)	6.06E+04	2.76E+04	4.24E+06	1.90E+06	SETX
	2.26E+03	3.60E+02	1.77E+05	2.80E+04	ELEC
	5.28E+03	4.30E+03	9.46E+05	7.42E+05	INFR
CO Emissions (tons/year)	5.70E+02	2.05E+02	4.01E+04	1.43E+04	SETX
	1.23E+01	3.1E-01	9.68E+02	2.43E+01	ELEC
	–	–	–	–	INFR
NO_X Emissions (tons/year)	8.16E+01	2.93E+01	5.71E+03	2.01E+03	SETX
	1.76E+00	7.70E-01	1.38E+02	6.08E+01	ELEC
	–	–	–	–	INFR
$PM_{2.5}$ Emissions (tons/year)	1.38E+01	4.98E+00	9.73E+02	3.47E+02	SETX
	2.99E-01	7.5E-03	2.35E+01	5.9E-01	ELEC
	–	–	–	–	INFR
PM_{10} Emissions (tons/year)	1.73E+01	6.22E+00	1.22E+03	4.34E+02	SETX
	3.73E-01	9.34E-03	2.94E+01	7.37E-01	ELEC
	–	–	–	–	INFR
ATR20 (K)	2.50E-07	1.20E-07	1.80E-05	7.90E-06	SETX
	0.94E-08	0.15E-08	0.74E-06	0.12E-06	ELEC
	1.05E-08	0.85E-08	1.66E-06	1.30E-06	INFR
ATR100 (K)	2.80E-06	1.30E-06	2.00E-04	8.80E-05	SETX
	1.05E-07	1.66E-08	8.23E-06	1.30E-06	ELEC
	5.25E-08	4.10E-08	8.06E-06	6.28E-06	INFR
Fuel consumption (litres/year)	2.38E+07	1.09E+07	1.67E+09	7.48E+08	SETX
	5.14E+05	–	4.03E+07	–	ELEC
	-	-	-	-	INFR

KPI	MXP case study		ECAC case study		
	BAU	With OIs	BAU	With OIs	
Energy consumption (kWh/year)	–	5.42E+06	–	3.91E+08	SETX
	–	1.54E+06	–	121.5E+06	ELEC
	2.60E+04	2.12E+04	4.66E+06	3.66E+06	INFR

A significant reduction of the emissions can be achieved thanks to the deployment of the three OIs under investigation. Not surprisingly, the largest effect is reached if all taxiing operations were to be performed with electric tow trucks, which have the potential to cut the CO_2 emissions by approximately a factor of 2.2. A significant contribution comes from the complete electrification of the GSE and operations, which can potentially cut the related emissions by about a factor of 6. A further contribution comes from the 23% reduction of the emissions generated from the generation of energy necessary for the heating, cooling, and lighting of the airport office buildings. Cumulatively, the combination of these three OIs can potentially reduce the overall contribution to the global warming of airports by approximately a factor of two. Considering MXP only, ATR20 and ATR100 would decrease to 0.13 μK and 1.4 μK, respectively. At European level, the impact of the airports would be reduced to 9.3μK in 20 years and 96μK in 100 years. In addition to the climate-impact mitigation, also the local air quality will significantly benefit from the transition away from fossil fuels. The emissions of pollutants such as carbon monoxide, nitrogen oxides, and particulate matter, are reduced in proportion to the amount of fuel that is saved for the different operations.

3. Discussion

The same sources of uncertainty that were identified for the individual OIs impact the results of the ground scenario (cf. Sect. A.6 – A.8). Also, an additional uncertainty of about 20% should be considered for the results of the simplified model developed in this context to estimate the impact of a completely electric tow taxiing. This uncertainty originates various strategies and assumptions that were necessary to enable the comparison of the results of the three OIs. These strategies include the choice of computing the fuel consumption for taxiing on a peak day at the MXP airport and then extrapolate this result for a whole year with an averaging factor of 0.8, and the three assumptions adopted to calculate the results at the ECAC level, as described in Sect. A.11.1. Another large source of uncertainty is to scale the ground fleet size and composition and the energy consumption for the office buildings calculated for the Milan airports using the number of flight operations as a proxy. This simple generalisation does not take into account, for example, the structural differences between seasonal airports and airports active the whole year. On average, the former are likely to have a larger ground fleet than the latter because it needs to be able to support the operations during the peak season, which will typically be significantly more numerous than the annual daily average. In addition, this generalisation does not consider airports where the administrative offices are part of the terminal buildings, and therefore the building structure and options for energy efficiency enhancement would be substantially different from those accounted for in this context. A detailed discussion of these aspects is presented in the sections relative to the individual OIs (Sect. A.6 – A.8)

Despite all uncertainties, this scenario clearly shows a great potential in terms of reducing the impact of airports on climate. While the overall contribution of the ground operations to the increase of the global temperature is relatively small even in the business-as-usual scenario, the results of this work show that a lot can be achieved as part of the collective effort of the aviation industry to become carbon neutral, and also for the improvement of the local air quality which would greatly benefit especially the airport operators and passengers. It should be emphasised that the proposed operational improvements do not simply move the location of the emissions from the airport ground to the location where the electric energy is produced, which would constitute an improvement of the local air quality but would not make a difference in terms of climate impact. Instead, we emphasise that by the means of the three proposed OIs there is a net mitigation of the overall climate impact of the airports. This mitigation effect is larger, the cleaner the source of electric-energy generation is. In the best-case situation in which all electric energy comes from renewable sources, the total emissions of CO_2 and other GHGs can be reduced by approximately a factor of two. Emissions cannot be completely eliminated because aircraft need to warm up their engines for a few minutes before departure, and to cool them down after landing.

In terms of feasibility, the main limitations to this scenario are not technical, as the three OIs are based on mature technology, but rather economic and operational. Large investments are necessary to deploy the three OIs, as they all require, at different levels, a change to the airport infrastructure. For example, to enable electric towing it is necessary to purchase a sufficiently large fleet of electric tugs to guarantee efficient taxiing operations and also to redesign the airport ground to create specific areas for coupling and decoupling the tugs. Charging stations would be required for the tow trucks and all other electric vehicles and equipment. Also, the number of movements in the terminal manoeuvring area will increase because the tugs will need to reach their position to tow the departing and landing aircraft. All electric vehicles will need to move to and from the charging stations for refill more frequently than fossil-fuel-based vehicles currently do. These additional movements will consequently increase the workload for drivers and air traffic controllers. In addition, the airport operations would change in ways that could potentially alter the costs and revenues of different stakeholders. For example, electric towing would imply reduced fuel costs for the airlines but additional costs for the stakeholder responsible for the taxiing operations. Taxiing could become a service that the airports offer to aircraft operators, or which could be outsourced to external companies specialised in this. Similarly for ground-handling vehicles, which could in principle be both owned by the airport or by multiple stakeholders but will need to recharge in special areas that need to be created and managed most likely by the airport operator.

The stakeholders can partly return on their investments thanks to the reduced costs for maintenance and purchase of energy. However, the time necessary to break even largely depends on the energy and fuel costs. The recent months, particularly after the escalation of the war in Ukraine, have shown that the cost of energy is volatile and has more than doubled in the last year, while that of fossil fuels has not increased by the same amount. This suggests that the implementation of the ground scenario, while technically feasible, is not a low-hanging fruit. It will thus require strong support from public entities to make it sustainable and thus encourage the stakeholders to contribute to the transition.

4. Conclusions

The ground scenario presented here describes a methodology to quantify the climate impact of an airport and how much this can be reduced by electrifying airport GSE and operations, including taxiing, and by enhancing the energy efficiency of the airport office buildings. The purpose of developing this scenario was twofold. On the one hand, it enables a direct comparison of the climate impact of different OIs. In addition, it gives an estimate of the extent to which airports and airport operations contribute to global warming. The key results of this scenario are that approximately 89% of the emissions related with ground operations and infrastructure come from the taxiing operations. Approximately two-thirds of the remaining emissions are related with the generation of energy necessary for the heating, cooling, and illumination of the airport office buildings, and one-third for the GSE and ground handling operations. The greatest emission reduction, a factor of about 6, can be achieved by electrifying this latter component. Electric towing has the potential to approximately halve the emissions from taxiing, whereas enhancing the energy efficiency of the buildings can reduce the yearly energy consumption, and thus the related emissions, by 20%.

In this scenario, the contribution to global warming of a mid-size airport such as MXP is reduced to ATR20=0.13 μK in 20 years and ATR100=1.4 μK in 100 years, about a factor of two lower than in a business-as-usual scenario. Extrapolating these results to the ECAC area, the cumulative contribution to global warming of all European airports can be estimated at ATR20=9.4 μK in 20 years and ATR100=96.6 μK in 100 years. Despite the large uncertainties that are involved in the modelling of these three different OIs and to enable a direct comparison, these results show that the proposed OIs have the potential to significantly reduce the overall climate impact of ground operations and airport infrastructure.

A.10 Network-operation scenario

Climate-optimal configuration of intermediate stop operations (ISO) is strongly influenced by the selection of the flight level and thus interferes with climate mitigation effects of flying lower. Previous research on ISO concepts, e.g. [22][23], aims at optimising fuel efficiency, which typically leads to higher flight altitudes due to reduced aircraft weights (Figure 52). Consequently, aircraft emissions are released at higher and, hence, more climate-sensitive areas. That is why climate optimised ISO additionally considers different flight levels (see Section 2.1 and 2.5, and A.1 and A.5).

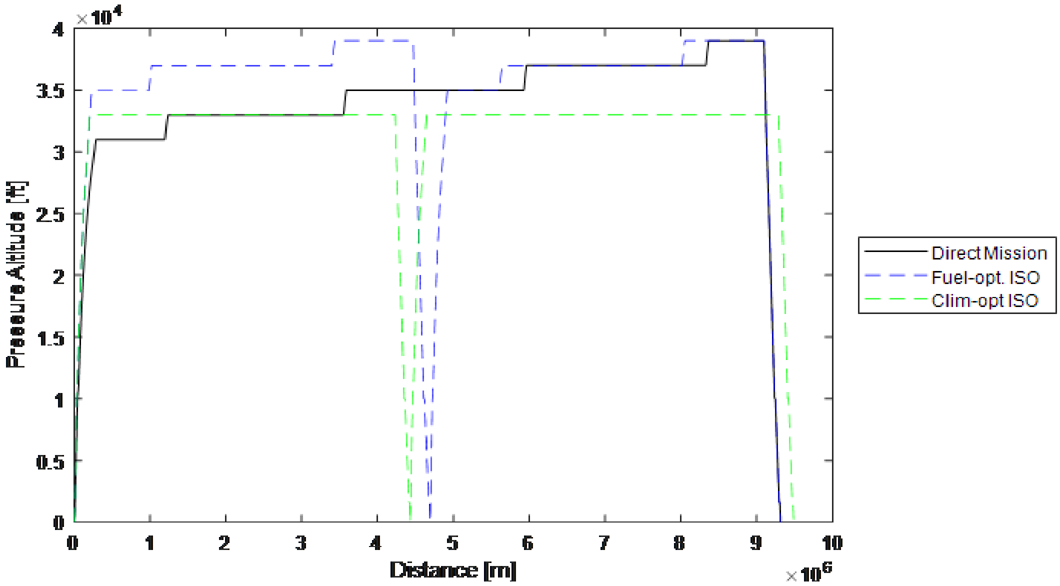


Figure 52. Higher flight levels for fuel-optimal ISO operations compared to the reference case and climate-optimal mission show interdependence between climate-optimised ISO and flying lower.

Furthermore, intermediate stop operation leads to an increase in flight time as well as in fuel consumption, which implicates higher direct operating cost (DOC) on the one hand, but also affects the airline network on the other hand. Longer flight times can lead to necessary adjustments in the network and higher DOC influence configurations of optimal networks. This relation is further intensified if lower flight levels with higher fuel consumption are selected. These intersecting effects are subject to the following study, that integrated climate mitigation potentials from LOSL, NETW and ISOC.

The modelling approach of this integrated study is based on tools and workflows applied in the studies focussing the individual OIs. The combined workflow is displayed in Figure 53. Different flight altitudes are considered as input variables for configuration of climate-optimised intermediate stop operations. Relevant KPIs (such as fuel consumption, trip time and average temperature response) are calculated for non-stop missions and ISO with a pre-selected intermediate stop airports as well as different cruise altitudes per combination of origin, destination, and aircraft. Results are then fed into the network optimisation, which aims to identify climate optimal network set-ups.

Figure 53. Connection of LOSL and NETW to ISOC

To ensure comparability of results, input data for modelling this integrated scenario is oriented towards the network-related OIs of NETW and ISOC. For this purpose, three representative airlines are selected (KLM, TAP, and easyJet, see Section 2.4 and A.4 for more details) in a way that major hub-and-spoke, secondary hub-and-spoke as well as point-to-point approaches are covered by the sample.

Based on the airlines' available fleet and possible combinations of origin and destination pairs (OD pairs), a synthetic flight plan is created that combines all possible OD pairs with all possible aircraft types. Furthermore, three different flight levels are considered. For all missions with a great circle distance of more than 2500 NM, ISO operations are considered in addition to non-stop connections. Consequently, the modelling flight plan is defined by the following options per OD pair and airline:

- **Aircraft type:** All aircraft types of the selected airline are modelled for every possible OD pair. Due to flight performance restrictions, not all combinations can be performed (e.g. long-distance flights with short-haul aircraft)
- Flight level: Three different specifications of flight level are considered. The fuel-optimal reference is modelled by incorporating fuel-optimal changes of the flight level during the flight (i.e. step climbs). In addition, two constant flight levels at 31,000ft and 37,000ft are considered
- **ISO mission:** For long-haul missions, three possible options are considered: Non-stop mission, an ISO mission with a fuel-optimal intermediate stop and an ISO mission with a stop at the climate-optimal ISO airport. Respective ISO airports are derived from results of the individual ISOC study (see Section 2.5 and A.5). For shorter missions, where benefits of ISO are limited, only direct connections are assumed.
- **Airline**: only KLM was considered to be investigated for the integrated scenario, as it has a diverse fleet and destinations which could reveal more of the potentials of this scenario.

<u>Trajectory, Emissions and Climate impact modelling</u>

To model characteristic KPIs (fuel burn, trip time, emissions and ATR), the ISOC (see Section 2.5 and A.5) workflow is applied:

1. DLR's TCM is applied to calculate four-dimensional trajectories for respective combinations of origin, destination, aircraft type, flight level and ISO mission. For this purpose, great circle connections and International Standard Atmosphere (ISA) are assumed. We apply BADA4 performance data [35] and an average European load factor of 0.84 [34]. If a mission cannot be performed due to weight restrictions, the load factor is adjusted to 0.63.
2. Emission quantities and their gridding is performed with DLR's GRIDLAB tool. In this context, DLR Fuel flow method [12] is applied to calculate emission quantities before they are summarised in a global emissions grid, which are the basis for climate metric calculations.
3. To simulate climate response, climate chemistry response model AirClim [18][46] is applied to calculate both ATR20 and ATR100 individually per mission.

The results are summarised in a comprehensive look-up table containing fuel burn, flight time, emission quantities, ATR20, and ATR100 per OD pair, aircraft type, flight level and ISO mission. This is the basis for the following analysis.

Assessment of climate KPIs

In this section, we have compared the implications of implementing ISO + LOSL compared to only direct flights when AOMAS optimises for ATR20 and Profit simultaneously.

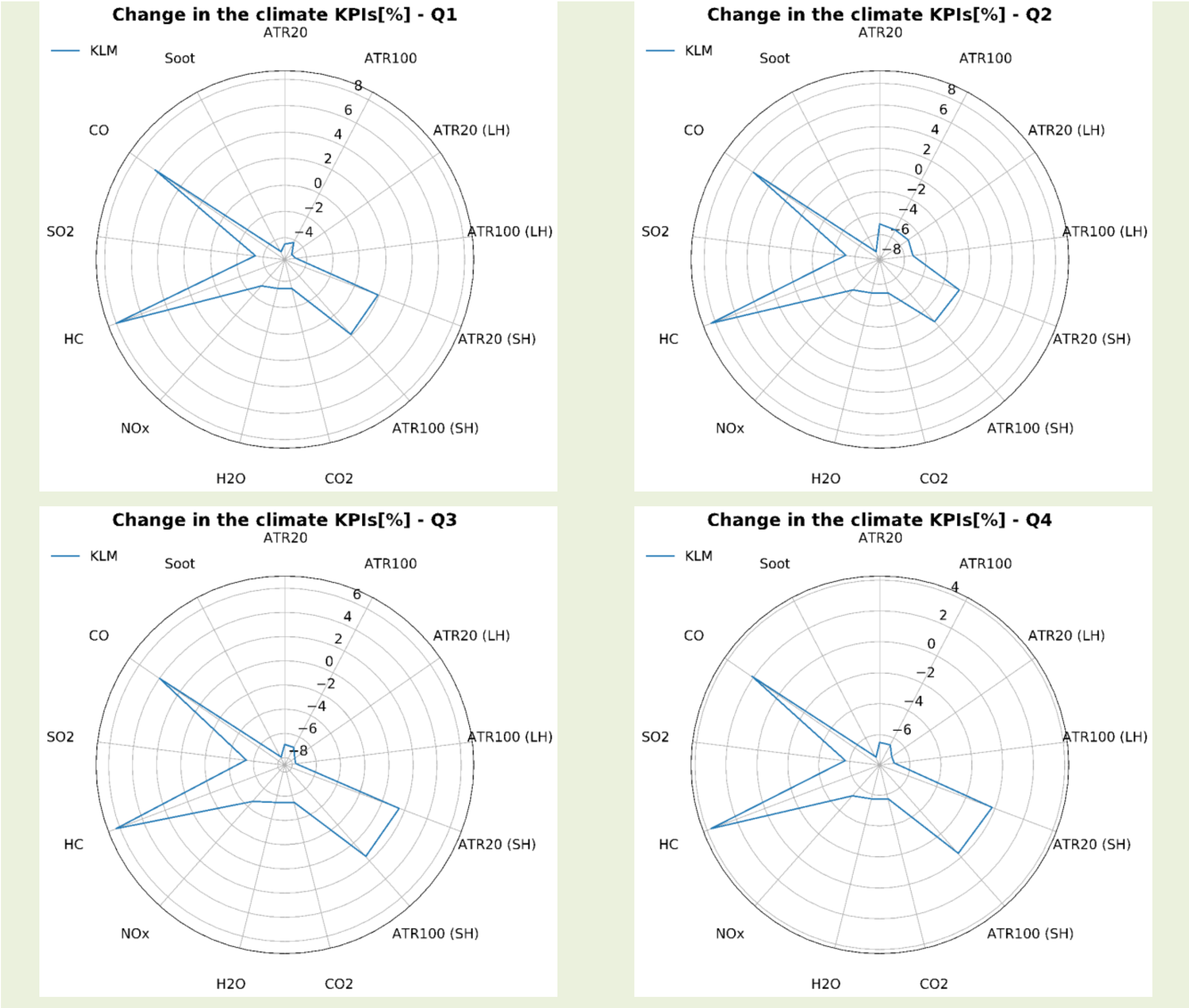


Figure 54. Implication of implementing ISO in the climate KPIs

We see a significant reduction of ATR20 we AOMAS allowed to implement ISO. The reduction varies from 4 to 9 percent based on the year's quarter. The pattern of the following figures is the same for all quarters, which suggests that additional landing and take-off in the ISO would increase the CO and HC KPIs, but the reduction in the other emission species is high enough to make the entire flights of the network greener.

Implementing ISOs has a network effect on short-haul flights as well. Two possibilities could happen based on the demand distribution of the network:

- Narrow-body aircraft are used to fly on medium to long-haul routes. In this case, the total ATR20 for short-haul flights will decrease as fewer aircraft are assigned to the short-range routes.
- Secondly, if some short-haul flights are highly profitable (either to have a very high demand or high yield), the vacancy of the narrow-body aircraft will be filled with wide-bodies which have much more ATR20 compared to a narrow-body on the same route. In this case, the total ATR20 of short-haul flights will be increased

Table 61. Climate impact improvement [mK] after implementing integrated scenario for KLM in 2018

	Q1	Q2	Q3	Q4	Total
ATR20	1.51E-2	2.11E-2	2.37E-2	2.23E-2	**8.22E-2**
ATR100	8.12E-3	1.40E-2	1.55E-2	1.45E-2	**5.21E-2**

Table 62. Climate impact changes [%] after implementing integrated scenario for KLM in 2018

	Q1	Q2	Q3	Q4	Total
ATR20	-4.9	-6.9	-7.1	-6.7	**-6.4**
ATR100	-4.1	-7.1	-7.2	-6.8	**-6.3**

Assessment of non-climate KPIs

As ISO operation has a longer flight time, the utilisation of the fleet will increase. In general, increasing the utilisation is a potential sign of making more profit. But in this case, the increase in utilisation comes from longer flight time, which will not lead to more pax served and more profit. On the other hand, increasing flight time made 3-5% of the long-haul flights unprofitable. The reduction in the revenue of long-haul flights may be caused by the previously missing connecting passengers or the inability to make a connecting flight with the other flights at the connection bank.

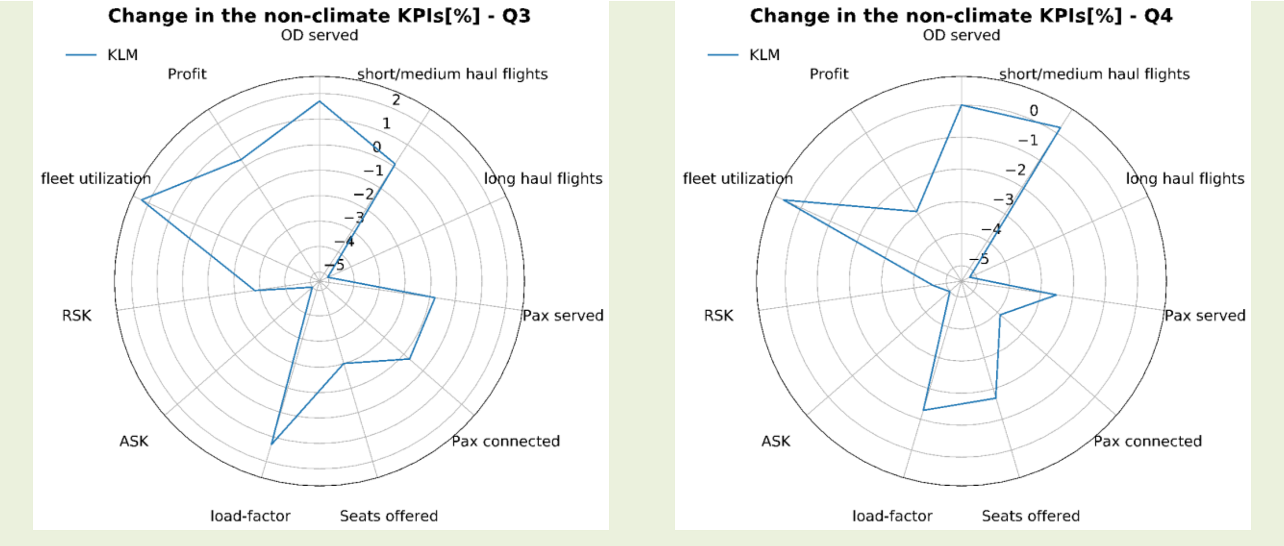


Figure 55. Implication of implementing ISO in the non-climate KPIs

The ISO operation is more efficient in the fuel and, as a result, cheaper economically. In this case study, allowing ISO would help AOMAS to find a solution with a much lower ATR20, while the profit decrease is slightly different compared to the same setup without ISO. In other words, ISO could compensate for a part of the profit lost due to operating in a more climate-friendly network.

Uncertainty estimate

Uncertainties can be assessed according to the individual studies that are combined to the integrated workflow. Major uncertainties to be considered are:

- Uncertainties in trajectory and emissions modelling: Application of an average load factor, BADA4 flight performance characteristics, and ISA influence results. However, the resulting uncertainties are estimated to have only a minor impact on the results.
- Uncertainties in climate impact modelling: Model development and application of AirClim additionally goes along with uncertainties. Especially climate-impact from non-CO_2 emissions underlie significant uncertainties (see [46] for more details).
- DOC was calculated based on the fuel flow and average share of the fuel cost in the
- Network uncertainties

Comparability of the results with the other OIs

Different considered airline types allow a scaling of results to the full European scale based on their distribution along European operators. Besides that, no additional restrictions regarding aircraft type, geographical or temporal scope were taken, which ensures comparability of results. Due to the chosen simulation approach especially in terms of climate response modelling, a direct comparison with the individual OIs of ISOC and NETW is possible. A comparison with ground-related and trajectory related OIs is limited due to different approaches in climate impact modelling, e.g. with aCCFs. Nevertheless, relative mitigation potentials in terms of ATR and order of magnitude comparison of absolute values can be performed.

The modelling setup is the same as the one used in the NETW OI. So, no additional restrictions take place in this case study. Same point which was mentioned in the NETW holds here as well.

Applicability of the OI

Applicability of this integrated scenario is mainly determined by feasibility of respective individual OIs:

- Flying lower increases utilisation of lower, more climate-friendly airspaces. An upgrade in CNS infrastructure will support implementation and ensure high safety levels at the same time.
- ISO comes along with additional starts and landing per mission and at an intermediate stop airport. Some of these airports are not able to handle large amounts of additional starts and landings that will be required when implementing the concept on a broader scale. Thus, an upgrade in the infrastructure of those airports will facilitate an implementation of the ISO concept.
- Climate-optimised ISO concept does not only focus on fuel efficiency and resulting mitigation of CO_2 climate effects, but also aims to a reduction in non-CO_2 effects. The current regulatory is focussed on CO_2 effects only and thus penalises avoidance of non-CO_2 effects, if fuel efficiency decreases. This needs to be addressed from a regulatory perspective to increase the attractiveness of implementing these concepts.
- Changing the flight time and additional landing and take-off may have a result on the passenger demand and result in a very low demand, which does not fly in that route anymore.

Conclusions

NETW and ISO are individually effective in mitigating climate impact at the network level. combining these two OIs, including additional insights from LOSO, offers a promising compound effect. By adding ISO options to all medium to long-haul flights, the flexibility to obtain a new network plan will increase exponentially. Such flexibility will lead to a more ATR20 reduction while keeping the profit almost the same compared to the case in which ISO is not allowed.

Furthermore, ISO will also have a high effect on the other network KPIs. The most affected KPIs are connecting passengers and the number of long-haul flights, which decreased by 3.5 and 4.9 percent, respectively. As we have studied the ISO while optimising for ATR20 and profit, not all the reduction in the number of long-haul flights is caused by ISO operation, but the effect of missing connections due to longer flight time could be easily seen in the current result.

Appendix B: Human Performance Assessment: Objectives and Approach

All the Human Performance Assessment applied in the ClimOP project follows the Objectives and Approach detailed hereby. Human Performance (HP) refers to an individual's ability to successfully accomplish tasks and meet job requirements. A human's ability to complete a task successfully is an outcome of a number of variables that are assessed within the field of Human Factors (HF). These variables are: procedure and task design, design of technical systems and tools, the physical work environment, individual competences and training background as well as recruitment and staffing. HP also depends on the way in which social factors and issues related to change & transition are handled. In order to achieve benefits from Key Performance Areas (KPAs), HF and HP must be adequately considered in all phases of development and implementation.

Furthermore, HP assessment aims to offer assurance that HP aspects associated with technical or operational developments are systematically identified and managed, and that all actions necessary to provide enough confidence that products, services or systems are compatible with human abilities are undertaken.

The ClimOP project applied the SESAR Joint Undertaking HP Assessment [65] to three operational improvements to provide a high-level analysis of the impact such operational improvements will have on the human actors involved:

- Free routing and wind-optimised flight planning in high-complexity airspace (cf. Sect. A.2)
- Strategic planning (cf. Sect. A.4), and
- Single-engine/hybrid taxiing and e-taxi (cf. Sect. A.6).

The HP process consisted of 4 main steps [66]: 1) Understand the OI concept; 2) Understand its HP implications; 3) validate and improve from an HF perspective the OI concept; 4) Collate findings and support implementation and deployment phases (or, more generally, the reaching of higher maturity levels of the OI). The methods of data collections and analysis consisted in focus groups with the Advisory Board members, desk research, task analysis, surveys and interviews with subject experts. The results of each HP assessment are detailed in the Appendix of the addressed OI.

The purpose of this assessments is to contribute at the evaluation of the proposed solutions by considering non-climate KPIs. The HP assessment will therefore help enlarge the perspective on the perks and disadvantages associated with each ClimOP operational improvement. More extensive human performance analysis may be needed for the implementation of such measures.

Appendix C: Analysis of the Social Acceptance Survey

C.1 Design

The successful implementation of any climate-friendly measure will also depend on the degree to which the society is willing to accept such a measure. A survey was therefore devised to investigate the social acceptance of the operational improvements analysed in ClimOP. The purpose of this survey is to analyse the social aspects that influence the acceptance of "green" technologies and measures, in addition to the technical and economic aspects described in the previous sections. OIs that are technically and economically feasible in a given context may not be successfully deployed because of e.g. social resistance or lack of awareness of the technology. The most relevant aspects to be investigated in the ClimOP context were partly adapted from prior studies on the social acceptance of renewable energies [67][68][69][70] and combined with individual psychological factors. In the following, the main aspects considered in devising the ClimOP social acceptance survey are summarised.

Social Acceptance is intended as a positive attitude towards a technology or measure, which leads to a supporting behaviour towards it, especially 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 (e.g. adopting OIs). In this context, attitude is intended as the degree to which a person has a favourable or unfavourable evaluation of the said behaviour [71]. 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 environmentally sustainable behaviours would want to share with its citizens values and norms on global and environmental issues. People who share or internalise these behaviours are the first ones to adopt new "green" solutions on a personal and social level. This effect is stronger if, when reflecting on past experiences and anticipating future obstacles, behaviours are perceived as controllable, favourable, and implementable.

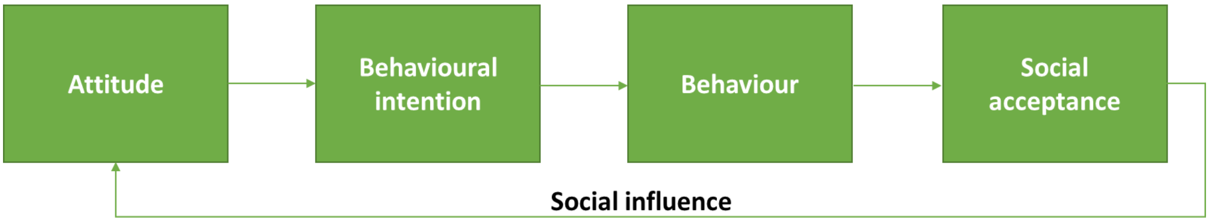


Diagram of the relations between attitude, behavioural intention, behaviour, and social acceptance.

An additional aspect to be considered is that most innovative technologies for sustainability 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 [67]. 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 [72] 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.

C.2 Distribution

The “ClimOP Survey for aviation passengers” assessed the social and individual aspects influencing the acceptance of OIs. Moreover, the survey promoted the awareness of operational improvements. Its main objective is to understand acceptance levels and track how they change across different segments of respondents, distributed in European Member States.

The survey was distributed between the end of 2021 and early 2022 through two different channels:

- Google Form version: a first version has been realized on the google platform and has been distributed within the consortium. A snowball sampling has been performed.
- Survey Monkey version: the same survey version has been implemented in the Survey Monkey platform where collectors for specific nations have been created. The answers were collected considering the EU population ratio to be able to generalise the results.

The questionnaire was distributed across a wide base of general audience through Survey Monkey. Respondents have been chosen in relation to European countries ratio: Italy, the Netherlands, the United Kingdom, Germany, Greece, France, and Spain.

C.3 Methodology

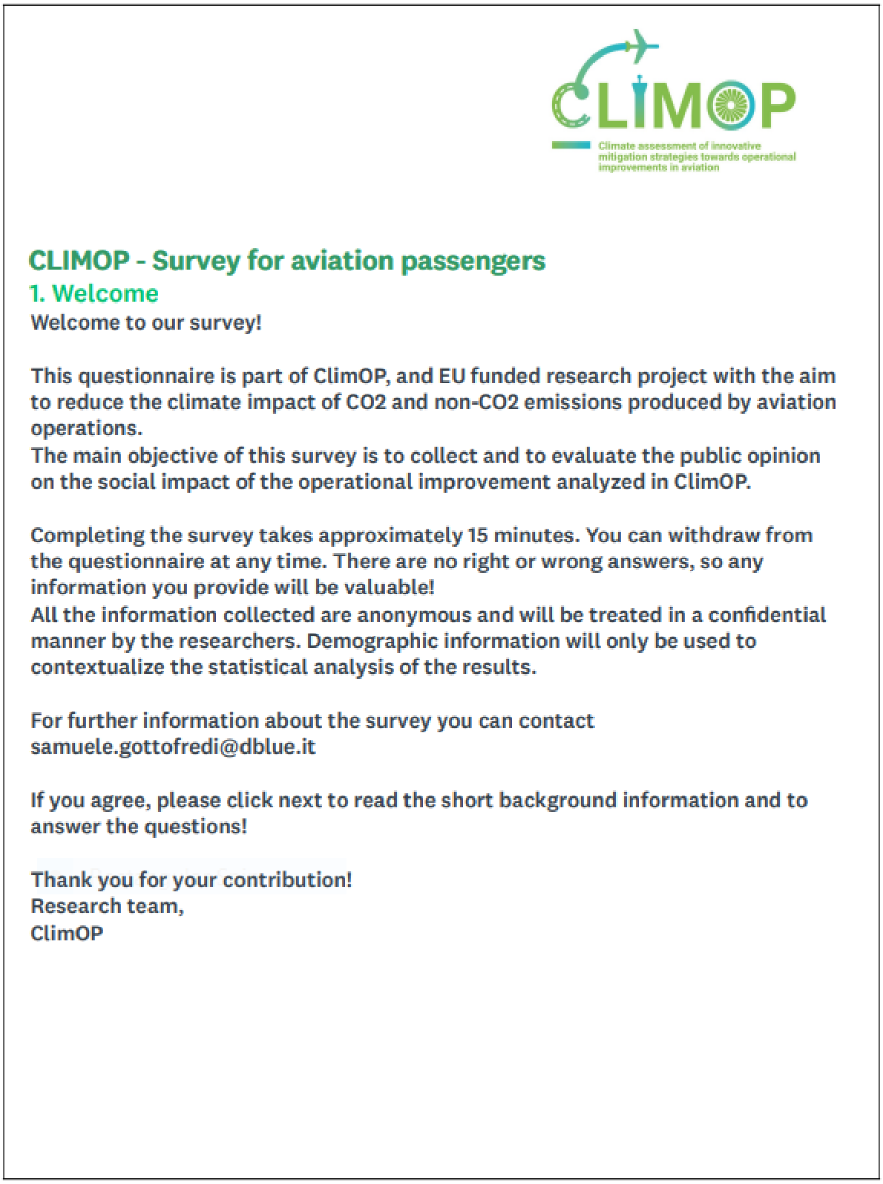
The survey was composed of 37 questions, organised around the factors described in section C.1. The survey presented ten close-ended questions, 21 items requiring the respondents to declare the level of agreement on a 5-point Likert scale, and six open-ended questions. Examples of the items can be seen in table 45.

Table 45. Example items.

Item category	Item example	Response example
Close ended	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?	< 10 10 - 30 30 - 50 50 - 70

		70 - 90 > 90
Open ended	15. On a daily basis, which decisions do you take with the aim of preserving the environment?	Box for typing
Likert	29. How much would you be in favour of taking segmented flights with longer stop-overs to spend some time exploring the intermediate city?	1 absolutely not in favour 2 not in favour 3 neutral 4 in favour 5 absolutely in favour

The first part of the survey introduced the project and the aims of the survey as well as all the references to privacy policy, consent forms and GDPR compliance pages and information.



Climate assessment of innovative mitigation strategies towards operational improvements in aviation

CLIMOP - Survey for aviation passengers

1. Welcome

Welcome to our survey!

This questionnaire is part of ClimOP, and EU funded research project with the aim to reduce the climate impact of CO2 and non-CO2 emissions produced by aviation operations.
The main objective of this survey is to collect and to evaluate the public opinion on the social impact of the operational improvement analyzed in ClimOP.

Completing the survey takes approximately 15 minutes. You can withdraw from the questionnaire at any time. There are no right or wrong answers, so any information you provide will be valuable!
All the information collected are anonymous and will be treated in a confidential manner by the researchers. Demographic information will only be used to contextualize the statistical analysis of the results.

For further information about the survey you can contact samuele.gottofredi@dblue.it

If you agree, please click next to read the short background information and to answer the questions!

Thank you for your contribution!
Research team,
ClimOP

The second section collects six socio-demographic variables (such as: age, gender, country, education, income, and profession). This information was analysed in an aggregated and anonymised way.

The third part of the survey collects three questions about the “Travel habits”; four questions about the “Perception of Climate Change as an issue”; two questions about “Environmental friendly behaviours”; three questions about the “Awareness”; three questions about the “Perception of aviation impact on climate”; two questions about the “Interest in green mobility”; and 14 questions for “Operational Improvements”.

All the questions in the second and third part were mandatory, hence the respondent could not proceed with the survey if some item was not answered. When relevant, the option “other” was inserted to enable the respondent to express additional information or comment and integrate their responses. The survey has been distributed in English in January 2022 and reached 406 respondents (sample size *N*= 406). Additional information on the sample size will be given in section C.5.1. Background information. The plan for the statistical analysis is presented in section C.5. Survey analysis.

C.4 Expected outcomes

The comparison between initial and final answers, collected among the different segments of respondents, will inform the project Consortium about the project success in terms of:

- Awareness level concerning operational improvements in the aviation domain
- Acceptance level concerning operational improvements in the aviation domain
- Passengers’ engagement level linked to specific OIs

Both citizens and aviation stakeholders will benefit from the results. We strongly believe stakeholder engagement is truly efficient only if bottom-up flow of information is ensured, since it shortens the distance among domain experts and passengers. Indeed, it encourages the exchange of knowledge, needs and ambitions.

C.5 Survey Analysis

This section introduces the general Statistical Analysis Plan, together with the results of the statistical analysis. Depending on the nature of the variable considered, the data analysis process can be described as follows:

1. Calculate descriptive statistics for both independent (IV) and all dependent variables (DV). More precisely the IV and DV considered for the different analyses are described in paragraphs: 3.1 (Independent Variables); from 3.2 to 3.14 (Dependent Variables).
2. The mean (M) and standard deviation (SD) of the results are calculated for questions with answers measured on Likert scales. Also, parametric tests are performed to determine whether differences between the dependent variables are significant (one-way analysis of variance - ANOVA)
3. Spearman correlation coefficient will be used to measure the strength and direction of the association between dependent variables for each condition.
4. The open-ended questions will be used to gain insight for the conclusions.

Details on the statistical analysis performed for each variable, together with the results, are presented from section C.5.1 to C.5.14, while the Discussions are presented in Section C.6. and the Conclusions will be presented in Section C.7.

The statistical analysis was performed with the software package SPSS version 24.

C.5.1 Background information

The questions in this section focused on aspects which could influence individual behaviour related to operational improvements. These include age, income, level of education, and country of residence.

Q1 Age

Table 63. Age of the survey respondents.

Age	Frequency	Percentage	Cumulative percentage
18-24	48	11.8%	11.8%
25-34	142	35%	46.8%
35-44	101	24.9%	71.7%
45-54	57	14%	85.7%
55-64	40	9.9%	95.6%
65+	18	4.4%	100%
Tot	**406**	**100%**	**100%**

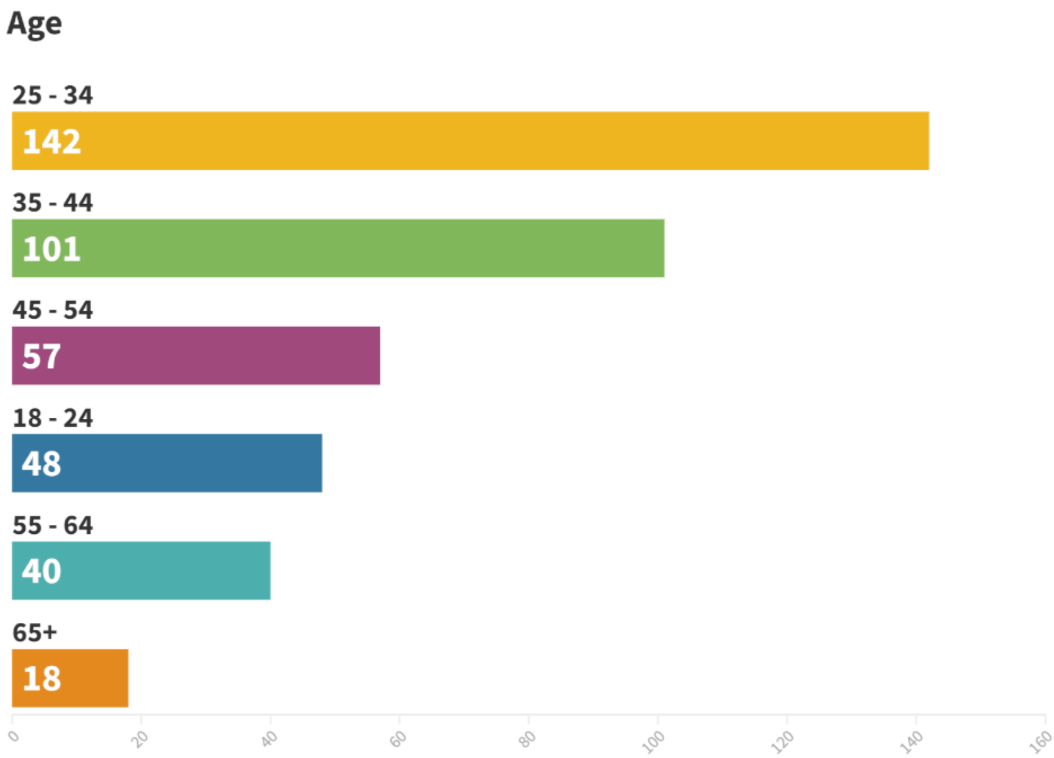


Figure 56. Age of the survey respondents.

Age distribution can be seen in Table 63 and Figure 56. At least ten respondents are present for each group. The younger participants (18-44) account for 71.7% of the total sample. The cluster of respondents is not representative of the EU population for the variable "Age" as the median age of the EU-27 population is 43.7 years (Data source: Eurostat, reference date: 1 January 2019). The higher likelihood of younger people to act against climate change may have influenced them to participate in this survey.

Q2 Gender

Table 64. Gender of the survey respondents

Gender	Frequency	Percentage	Cumulative percentage
Female	232	57.1%	57.1%
Male	170	41.9%	99%
Other	4	1%	100%
Tot	**406**	**100%**	**100%**

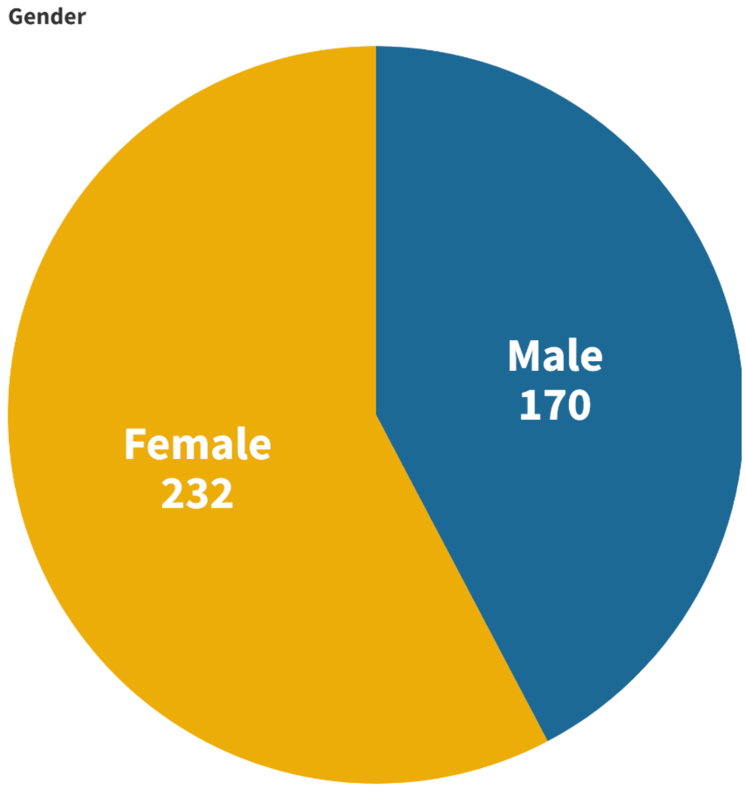


Figure 57. Gender distribution of the survey respondents

Gender distribution can be seen in Table 64 and Figure 57: females 57% and males 42%. These results are almost in line with the distribution of the EU population for the variable Gender. Age and gender will be used as independent variables.

Q3 Nationality

Table 65. Nationality of the survey respondents

Nation	Frequency	Percentage	Cumulative percentage
Italy	84	20.7%	20.7%
Germany	78	19.2%	62.1%
France	78	19.2%	82%
UK	75	18.5%	42.9%
Spain	52	12.8%	94.8%
Other	21	5.2%	100%
The Netherlands	15	3.7%	24.4%
Greece	3	0.7%	62.8%
Tot	**406**	**100%**	**100%**

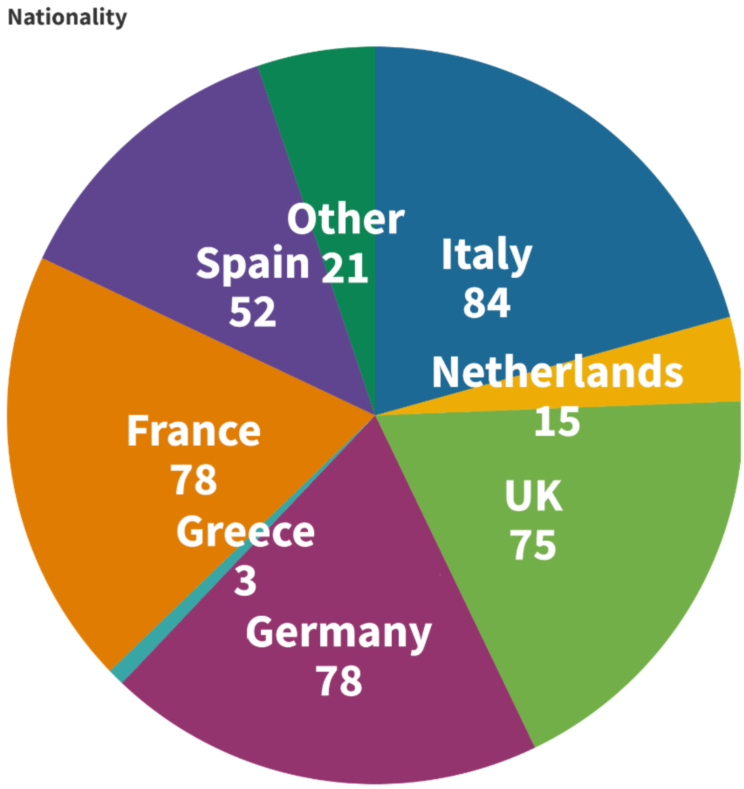


Figure 58. Nationality of the survey respondents

The geographical distribution of respondents' countries of residence is shown in Table 65 and Figure 58. Having the possibility to target respondents through the Survey Monkey platform, Countries have been selected, in accordance with European population ratio.

Q4 Education

Table 66. Education of the survey respondents

Education	Frequency	Percentage	Cumulative percentage
Middle school diploma	32	7.9%	7.9%
High school diploma	125	30.8%	38.7%
Bachelor's degree	97	23.9%	62.6%
Master's degree	119	29.3%	91.9%
PhD	33	8.1%	100%
Tot	406	100%	100%

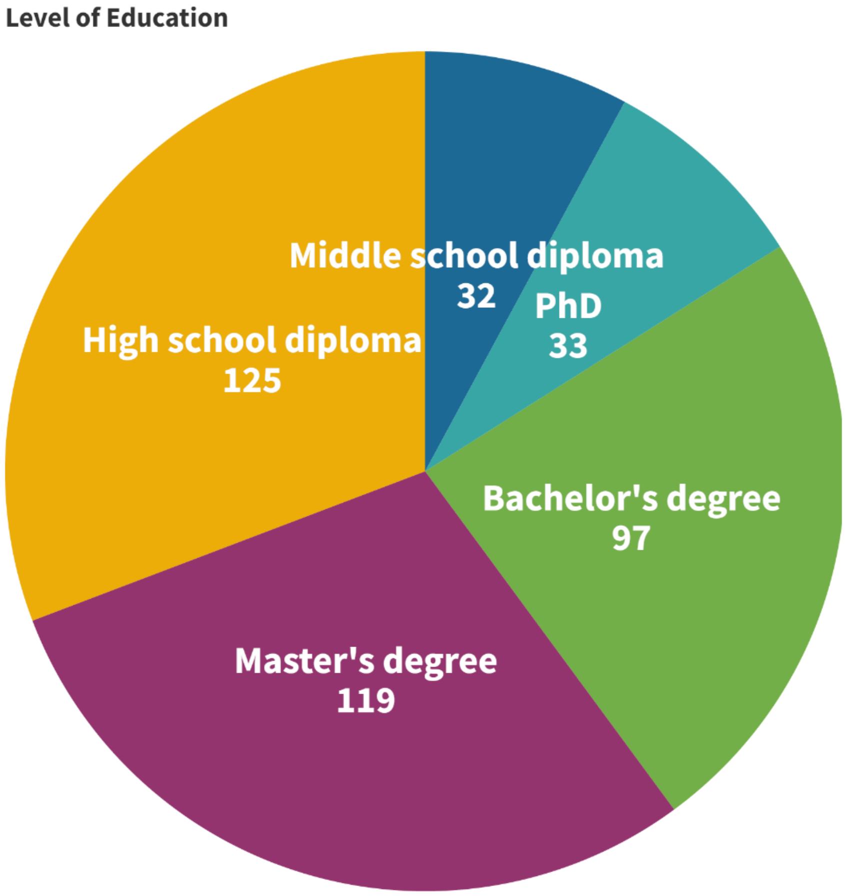


Figure 59. Education of the survey respondents

Respondents' education level varies between Middle school (*N*=32) and PhD (*N*=33), which are also the two less frequent groups. High school (*N*=125) and Master's degree (*N*=119) are the two most frequent categories, followed by Bachelor's degree (*N*=97). Respondents with at least one university diploma account for 61.33% (N=249).

Q5 Income

Table 67. Income of the survey respondents

Income	Frequency	Percentage	Cumulative percentage
< 20.000 €	114	28.1%	28.1%
20.000-40.000€	173	42.6%	70.7%
40.000-60.000€	104	25.6%	96.3%
> 60.000€	15	3.7%	100%
Tot	406	100%	100%

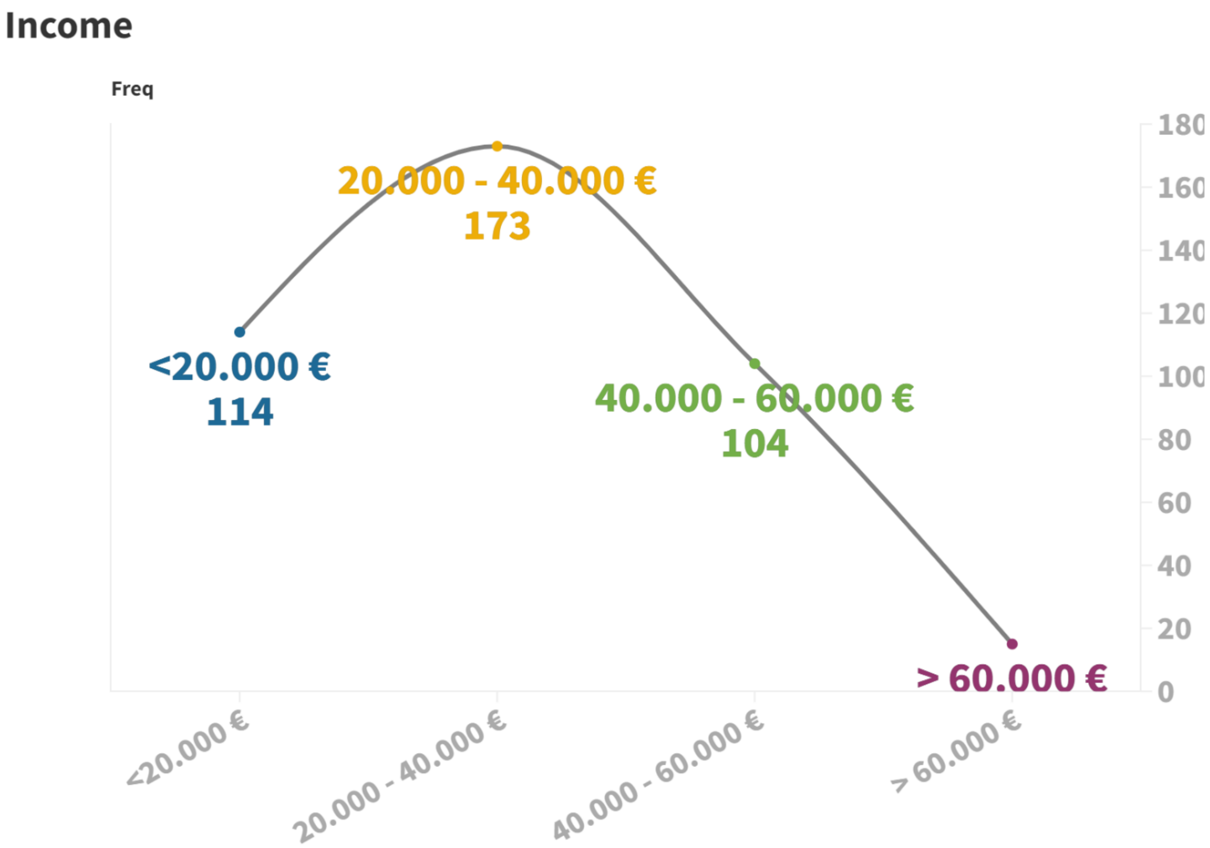


Figure 60. Income of the survey respondents

The most frequent income range for respondents is 20.000-40.000€ with 42.6% (N=173) of the total sample. The group with an income below 20.000 € follows (N=114) with almost the same frequency as the medium-high income group (40.000-60.000€, N=104). A small proportion of respondents (3.7%, N=15) report an income higher than 60.000€.

Q6 Profession

Table 68. Profession of the survey respondents

Profession	Frequency	Percentage	Cumulative percentage
Student	36	8.9%	8.9%
Teacher	27	6.7%	15.5%
Policymaker	5	1.2%	16.7%
Pilot	4	1.0%	17.7%
Marketing/Communication	37	9.1%	26.8%
Entrepreneur	15	3.7%	30.5%
Engineer	31	7.6%	38.2%
Energy/Environment consultant	6	1.5%	39.7%
Data analyst	12	3.0%	42.6%
Air Traffic Controller	5	1.2%	43.8%
Consultant/Researcher	49	12.1%	55.9%
Aerospace engineer	5	1.2%	57.1%
Other	174	42.9%	100%
Tot	**406**	**100%**	**100%**

Respondents' reported profession varies. The most frequent identified profession is Consultant/Researcher (N=49), followed by Marketing/Communication (N=37), Student (N=36) and Engineer (N=31). As many as 174 respondents answered "*Other*". Answer options were defined in function of profession that could be inherent with the aviation domain. So, 42.9% of the respondents are identifiable as 'general public', i.e. not involved in the aviation domain.

C.5.2 Travel habits

The questions in this section collected information about the most used and favourite means of transport, and airplane travel habits prior to the pandemic. The questions focused on identifying respondents' habits to better understand their relationship with flying and possible interest in OIs.

Q7 Most used means of transport

Table 69. Most used means of transport

Most used transport	Frequency	Percentage	Cumulative percentage
Car/Motorbike	260	64.0%	64.0%

Bike	40	9.9%	73.9%
Electric bike	9	2.2%	76.1%
Bus	46	11.3%	87.4%
Train	39	9.6%	97.0%
Airplane	4	1.0%	98.0%
Moped	3	.7%	98.8%
Electric Scooter	5	1.2%	100.0%
Tot	406	100%	100%

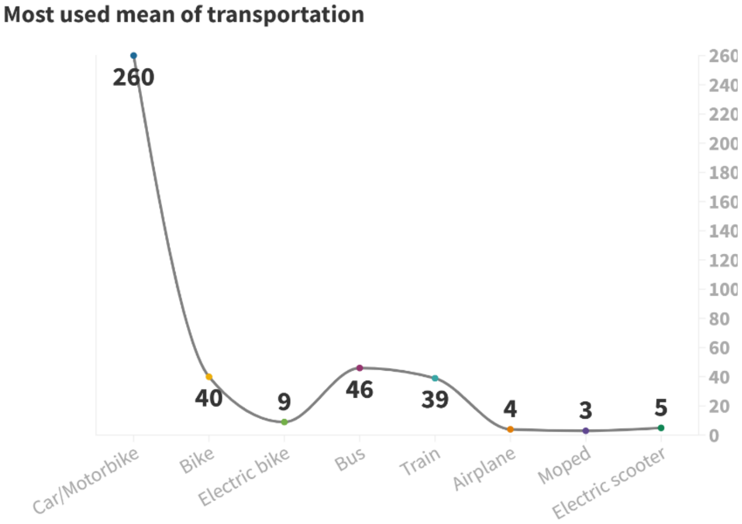


Figure 61. Most used means of transport

Car/motorbike (N=260) are the most-frequently used means of transport, followed by other motor vehicles such as Bus (N=46) and Train (N=39). A similar proportion of respondents (about 10%) uses bike as main transport mean (N=40). Only 1% of respondents use the Airplane (N=4) more than any other mean of transport. Results show how most of the respondents are still more likely to use fossil-fuel powered means of transport than any other solution.

Q8 Favourite transport

Table 70. Favourite mean of transport

Favourite transport	M	SD	Sum
Car/Motorbike	3.84	1.269	1559
Bike	3.18	1.233	1291
Electric bike	2.80	1.130	1137
Bus	2.69	1.106	1091
Train	3.42	1.083	1388
Airplane	3.21	1.118	1302
Moped	2.31	1.027	938
Electric Scooter	2.49	1.135	1012

The most-frequently used means of transport do not always correspond to the favourite ones. When asked to express preference for each mean of transport on a 5-point Likert scale, respondents' state to prefer "*Car and Motorbike*" as the favourite mean (mean *M*=3.84; standard deviation *SD*=1.27), followed by Train (M=3.42; SD=1.08), Airplane (M=3.21; SD=1.12) and Bike (M=3.18; SD=1.23). Figure 53 shows a clear tendency to private mobility (N=260) against shared means of transport. Moped is the least favourite means of transport (M=2.31; SD=1.03).

Q9 Airplane travel habits before pandemic

Table 71. Q9 Airplane travel habits before pandemic

Airplane travel	Frequency	Percentage	Cumulative percentage
Once a week or more	18	4.4%	4.4%
Two/three times month	35	8.6%	13.1%
Once a month	59	14.5%	27.6%
Two/four times a year	145	35.7%	63.3%
Once a year or less	149	36.7%	100.0%
Tot	**406**	**100%**	**100%**

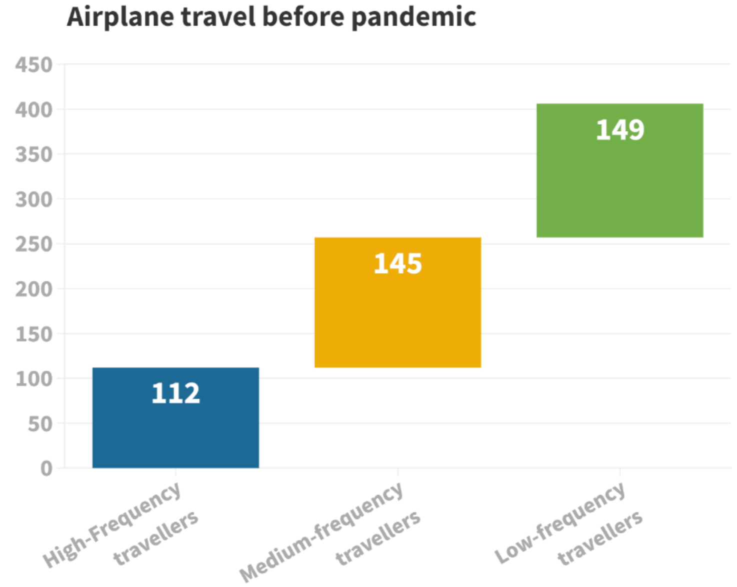


Figure 62. Airplane travel habits before pandemic

In question 9, respondents were asked about their flight travel explicitly referring to their habits before the COVID-19 pandemic period to avoid distortions because of the travel restrictions enforced at various levels in different countries since 2020. It should be noted that respondents could be biased because of the two-year gap between the survey and the last "normal" flight and travel behaviours. About one third of respondents (36.7%) reported to fly once a year or less before 2020 (N=149), 35.7% reported to fly two to four times a year (N=145). 27.6% of the sample is composed by regular travellers, flying once a month or more (N=112).

C.5.3 Perception of climate change as an issue

This section collected information about the individual perception of environmental issues, perception of climate change as an issue for themselves and the others, and favourability in taking actions aimed at mitigating climate change. The purpose of these questions is to identify possible correlations between the respondents' concern about environmental and climate matters and their level of acceptance for the ClimOP OIs.

Q10 Perception of environmental issues

Table 72. Perception of environmental issues.

Environmental issues	M	SD	Sum
Pollution	3.90	1.108	1585
Extreme weather	3.96	1.082	1607
Loss biodiversity	3.81	1.120	1548
Traffic congestion	3.54	1.055	1438
Waste disposal	3.76	1.045	1526

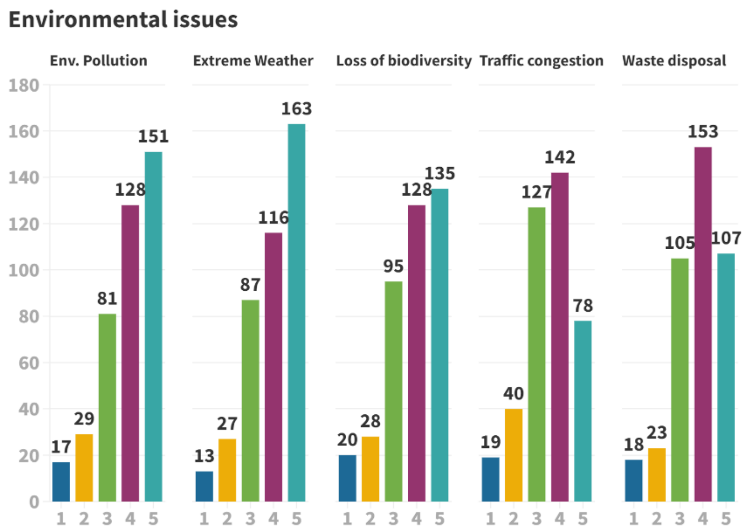


Figure 63. Perception of environmental issues

The respondents were asked to grade their concern for different environmental issues on a five-point Likert scale ranging from "very low" to "very high". All the presented environmental issues were identified as relevant issues. Extreme weather (M= 3.96; SD= 1.08) conditions and Pollution (M= 3.90; SD= 1.11) (e.g., water pollution, air pollution, soil pollution) have been identified as the two main concerns.

Q11 Perception climate change as an issue

Table 73. Perception of climate change as an issue

Climate issue	Frequency	Percentage	Cumulative percentage
Very low	11	2.7%	2.7%
Low	28	6.9%	9.6%
Neutral	66	16.3%	25.9%
High	90	22.2%	48.0%
Very high	211	52.0%	100.0%
Tot	406	100%	100%

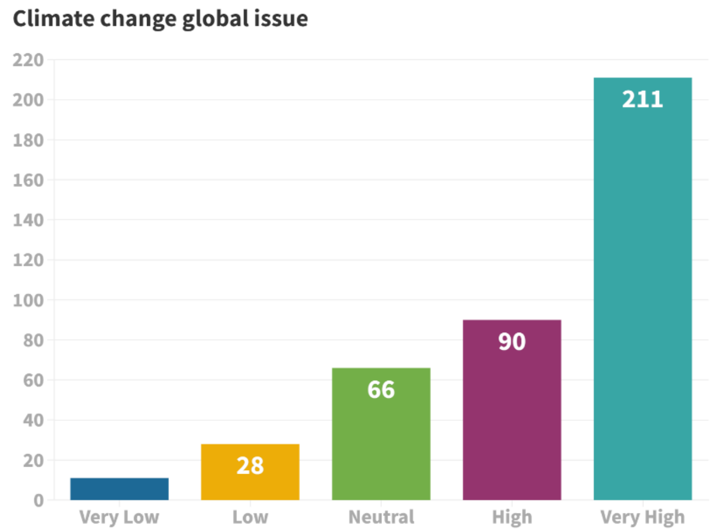


Figure 64. Climate change as global issue

More than half of the respondents (52%) expressed a very high concern for climate change (N=211). In general, 74.2% of the respondents expressed a high or very high concern for this issue.

Q12 Perception climate change as an issue for the others

Table 74. Perception of climate change as an issue for the people around me

Climate issue others	Frequency	Percentage	Cumulative percentage
Very low	13	3.2%	3.2%
Low	50	12.3%	15.5%
Neutral	130	32.0%	47.5%
High	140	34.5%	82.0%
Very high	73	18.0%	100.0%
Tot	406	100%	100%

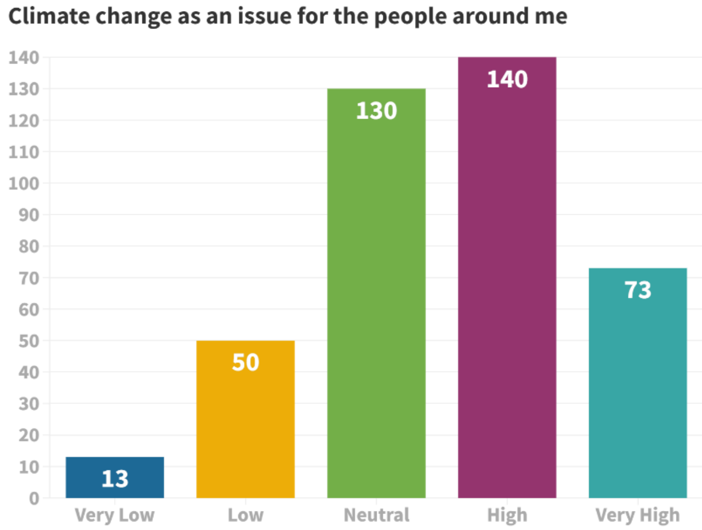


Figure 65. Climate change as an issue for the people around me

Question 12 reads “How much do you think climate change is an issue for the people around you?” The purpose of this question is to understand whether respondents expressing a given level of concern for climate change have the feeling that such concern is shared by the people they know and more in general by the society. On average, the results suggest that the respondents attribute a lower level of concern to the others than the one they express for themselves. According to the answers, about 52% of the people perceive climate change as a reason of “High” and “Very high” concern, that is a much lower proportion compared to the previous question. This perception bias is broadly in line with the Locus of Control Theory [73], according to which people tend to attribute the outcome of unpleasant events (such as a loss) externally, whereas they attribute internally those of pleasant (i.e., success). Therefore, people's individual perception is high (Q11), with high favourability of taking environmental actions (Q13), while others' perception (Q12) is lower.

Q13 In favour of taking actions to cope with climate change

Table 75. In favour of taking actions to cope with climate change

Mitigation actions	Frequency	Percentage	Cumulative percentage
Very low	8	2.0%	2.0%
Low	25	6.2%	8.1%
Neutral	93	22.9%	31.0%
High	118	29.1%	60.1%
Very high	162	39.9%	100.0%
Tot	**406**	**100%**	**100%**

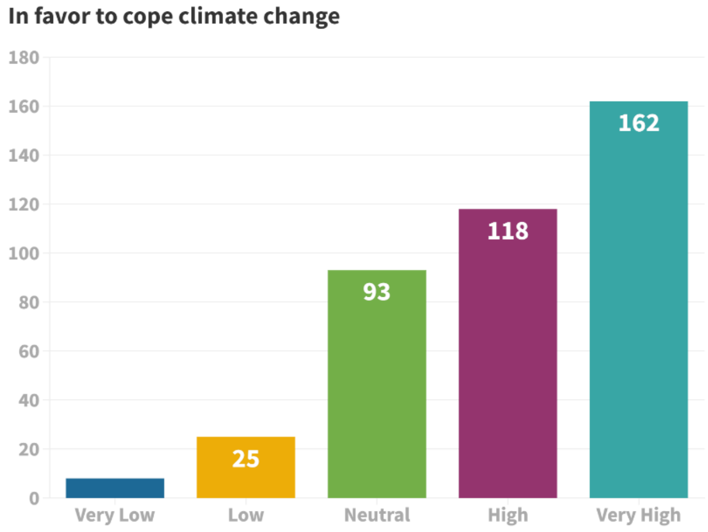


Figure 66. In favour to cope against climate change

In line with Q11, most respondents (69%) would be highly (N=118) or very highly (N=162) in favour of taking actions to cope with climate change.

C.5.4 Environmentally friendly behaviour

This section of the survey investigated whether the awareness about environmentally-responsible behaviours influences the decisions of the respondents and which decisions are taken to preserve the environment.

Q14 Awareness of environmental-responsible behaviours influence decision

Table 76. Awareness of environmental-responsible behaviours influence decision

PEB influence decision	Frequency	Percentage	Cumulative percentage
Very low	12	3.0	3.0
Low	46	11.3	14.3
Neutral	121	29.8	44.1
High	174	42.9	86.9
Very high	53	13.1	100.0
Tot	**406**	**100%**	**100%**

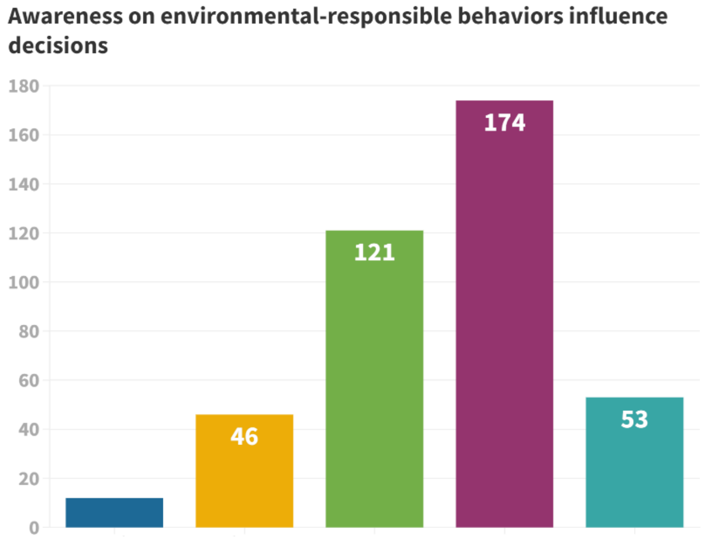


Figure 67. Awareness of environmental-responsible behaviours influence decision

Most respondents declare to have a high (N=174) or neutral/intermediate (N=121) level of awareness about environmentally-responsible behaviours.

Q15 Daily decisions to preserve environment

Table 77. Daily decisions to preserve environment

Decisions preserve	Frequency	Percentage	Cumulative percentage
0 decisions	108	26.6	26.6
1 decision	155	38.2	64.8
2 decisions	87	21.4	86.2
3 decisions	45	11.1	97.3
4 decisions	11	2.7	100.0
Tot	**406**	**100%**	**100%**

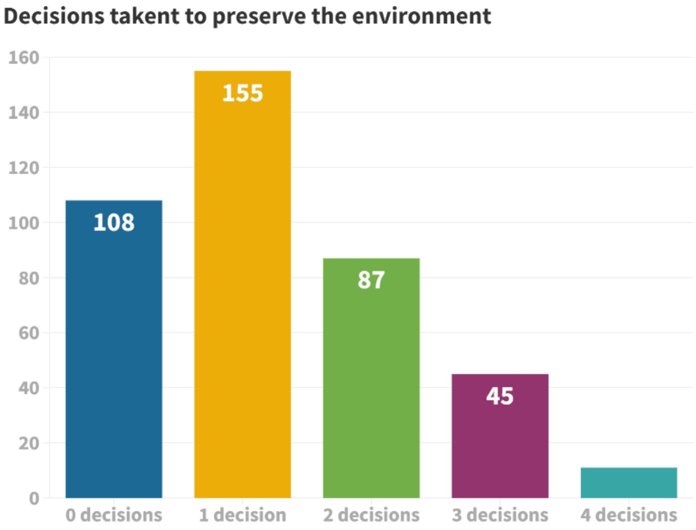


Figure 68. Daily decisions to preserve environment

Most respondents (N=155, 38%) daily take one decision aimed at preserving the environment. In partial contradiction with the results of the previous question 14, the second most frequent class are respondents that daily take no decision aimed at preserving the environment (N=108). This might suggest that many are aware of environmental issue but maybe this is not enough to drive their behaviours towards sustainability, or possibly that they do not consider actions such as using public transport, waste separation, or energy and water conservation as significant enough to be indicated in the survey.

The most cited decisions are:

- Energy conservation: electricity, water.
- Waste disposal
- Mobility behaviours: reduce personal car use, opting for public means of transport, bike or by foot (always as a function of the necessity: distance, reason of the movement, etc.)
- Pro-environmental behaviours: what to buy, reuse etc.

C.5.6 Awareness

This section aims to investigate the awareness of the general public about European, national and aviation initiatives to mitigate the climate impact of flying. The rationale behind these questions is that awareness is one of the main factors to influence someone’s behaviour and is necessary to induce a behavioural change.

Q16 Awareness European initiatives

Table 78. Awareness of EU initiatives

Aware euro initiatives	Frequency	Percentage	Cumulative percentage
0 initiatives	236	58.1	58.3
1 generic	75	18.5	76.8
1 specific	73	18.0	94.8
2 or 3 initiatives	14	3.4	98.3
More than 3	7	1.7	100.0
Tot	405	99.8%	100%

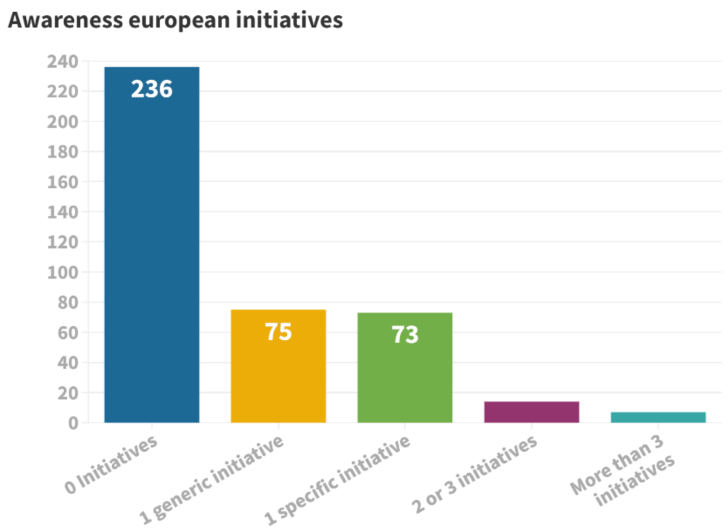


Figure 69. Awareness of EU initiatives

Q17 Awareness national initiatives

Table 79. Awareness of initiative at national level

Aware nation initiatives	Frequency	Percentage	Cumulative percentage
0 initiatives	239	58.9	59.0
1 generic	88	21.7	80.7
1 specific	62	15.3	96.0
2 initiatives	10	2.5	98.5
More than 2	6	1.5	100.0
Tot	405	99.8%	100%

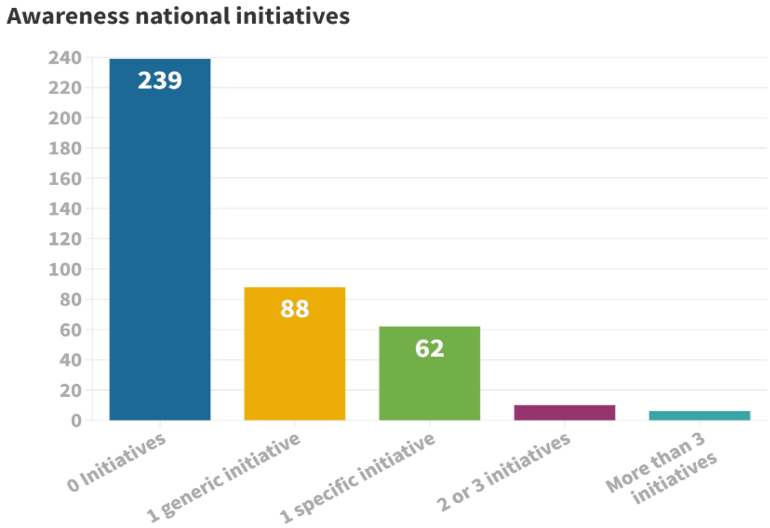


Figure 70. Awareness of initiative at national level

Q18 Awareness aviation initiatives

Table 80. Awareness of initiatives in the aviation sector

Aware aviation initiatives	Frequency	Percentage	Cumulative percentage
0 initiatives	310	76.4	76.5
1 generic	43	10.6	87.2
1 specific	28	6.9	94.1
2 initiatives	14	3.4	97.5
More than 2	10	2.5	100.0
Tot	405	99.8%	100%

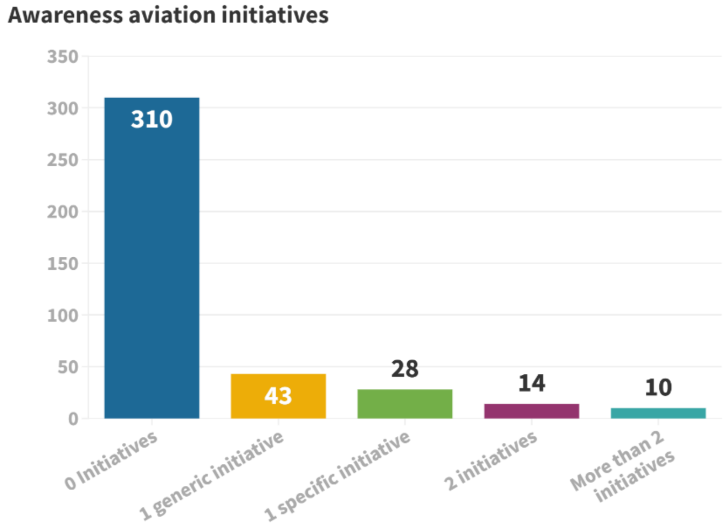


Figure 71. Awareness of initiatives in the aviation sector

Most respondents are not aware of any initiative, neither European (N=236), nor National (N=239) or aviation specific (N=310). While it is not unexpected that actions in the aviation domain are less known, as the respondents are mostly not aviation experts (cf. Sect. C.5.1), it is somewhat surprising that many respondents are unaware of sustainability initiatives. This might suggest that the communication and engagement campaigns need to be more widespread.

C.5.7 Perception of aviation impact on climate

The questions in this section investigate the perceived contribution of aviation to climate change. The total impact of human activities to climate change was nominally set to 100 and the respondents were asked to indicate the expected aviation share at present and in approximately thirty years. In addition, it was asked whether aviation should introduce measures to reduce its impact or not. The purpose of this section is to investigate whether the respondents have a correct picture of the aviation contribution to climate change, as this mode of transport has been frequently associated to a negative climate impact in the media.

Q19 Impact today 100

Table 81. Impact of aviation at the present day

Impact today 100	Frequency	Percentage	Cumulative percentage
< 10	79	19.5	19.5
10-30	113	27.8	47.3
30-50	98	24.1	71.4
50-70	88	21.7	93.1
70-90	16	3.9	97.0
>90	12	3.0	100.0
Tot	**406**	**100%**	**100%**

The total impact of aviation is currently between 2% and 5%, depending on the assumptions adopted for the estimate [1], hence the correct answer is "<10%". However, about 80% of the respondents was not aware or knowledgeable of this value. The largest respondent group identified 10-30% (27.8%; N=113) as the current percentage of the aviation impact on the total human impact, and more than half of the surveyed people believe that proportion of aviation among human activities is greater than 30%.

Q20 Impact 2050

Table 82. Impact of aviation by 2050

Impact 2050 100	Frequency	Percentage	Cumulative percentage
< 10	72	17.7	17.7
10-30	101	24.9	42.6
30-50	107	26.4	69.0
50-70	89	21.9	90.9

70-90	27	6.7	97.5
>90	10	2.5	100.0
Tot	**406**	**100%**	**100%**

The subsequent question asked to foresee the future impact of the aviation domain as a percentage of the total human impact on climate. The two largest respondent groups indicated that the share will be 30-50% (N=107) and 10-30% (N=101) of the total human impact, respectively. About a third of the sample believe that the total share of aviation will be larger than 50%, whereas the percentage of those believing that aviation will remain a minor contributor to climate change compared to other human activities does not change significantly compared to the previous question (approximately 18%).
The comparison of the mean values and standard deviations of the answers, the result is that the general perception about the aviation share does not change significantly for the current and future impact, although there is a tendency to believe such impact will increase.

Table 83. Means and Standard Deviations of Aviation Impact TODAY vs. 2050

Impact aviation	M	SD	Sum
Impact today 100	2.72	1.273	1103
Impact 2050 100	2.82	1.280	1146

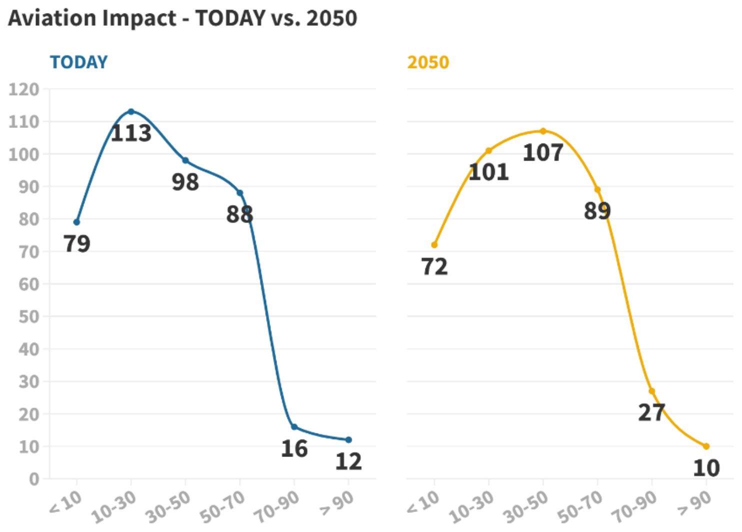


Figure 72. Aviation impact TODAY vs. 2050

Q21 Aviation needs mitigation measures

Table 84. Aviation needs mitigation measures

Aviation measures	Frequency	Percentage	Cumulative percentage
Totally disagree	22	5.4	5.4
Disagree	28	6.9	12.3
Neutral	111	27.3	39.7

Agree	127	31.3	70.9
Totally agree	118	29.1	100.0
Tot	406	100%	100%

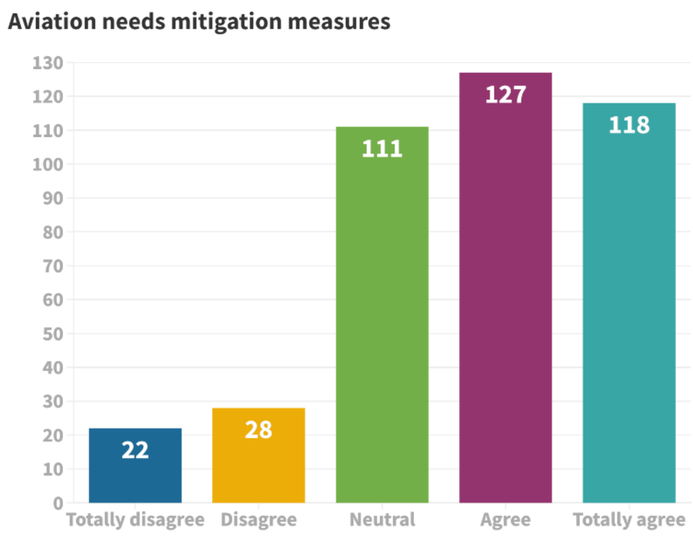


Figure 73. Aviation needs mitigation measures

The 60.4% of the respondents agree (N=127) or totally agree (N=118) that measures to reduce the aviation impact would be necessary, while 27.3% of respondents are neutral (N=111).

C.5.8 Interest in green mobility

The questions in this section collected information about the interest in rethinking their own mobility habits to foster climate change mitigation and their general interest in taking flights that in some way reduce the emissions of greenhouse gases.

Q22 Interest in rethinking mobility

Table 85. Interest in rethinking mobility

Rethinking mobility	Frequency	Percentage	Cumulative percentage
Totally disagree	25	6.2	6.2
Disagree	20	4.9	11.1
Neutral	94	23.2	34.2
Agree	155	38.2	72.4
Totally agree	112	27.6	100.0
Tot	406	100%	100%

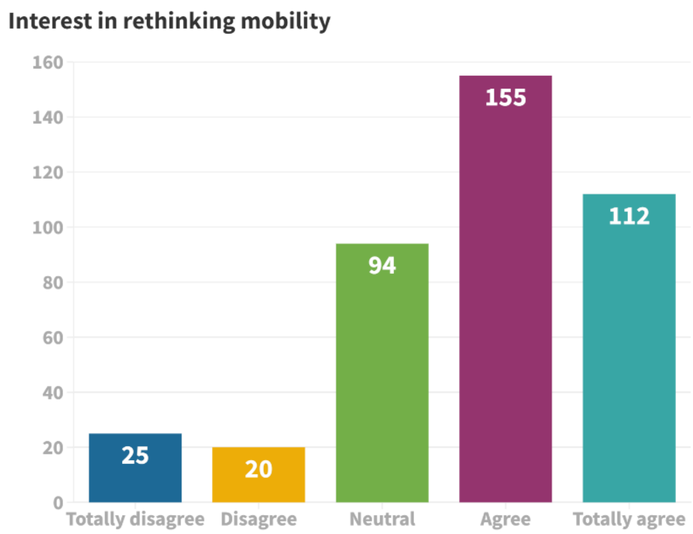


Figure 74. Interest in rethinking mobility

A great number of respondents are either very interested (N=112) or interested (N=155) in rethinking their mobility. Somewhat in line with other previous answers, not only respondents are aware of the general problem of the climate impact of transport but appear to be in favour of a change.

Q23 Importance of taking flights with reduced emissions

Table 86. Importance of taking flights with reduced emissions

Take flight with OIs	Frequency	Percentage	Cumulative percentage
Totally disagree	18	4.4	4.4
Disagree	23	5.7	10.1
Neutral	101	24.9	35.0
Agree	144	35.5	70.4
Totally agree	120	29.6	100.0
Tot	**406**	**100%**	**100%**

Importance of taking flights with reduced emissions

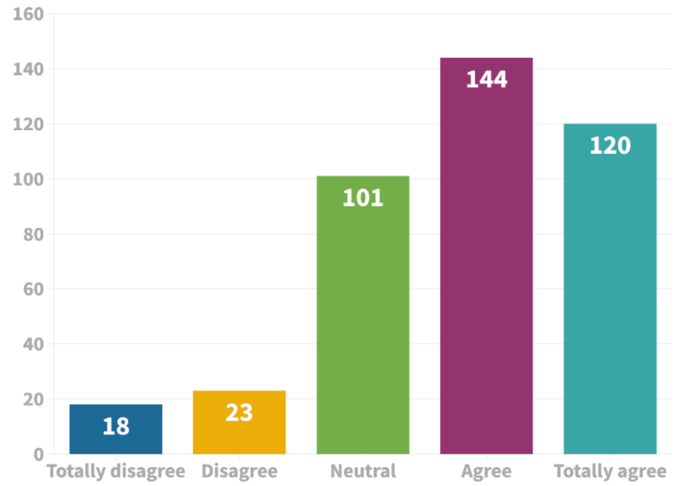


Figure 75. Importance of tacking flights with reduced emissions

An important portion of respondents totally agrees (N=120) or agrees (N=144) that taking it would be important to fly on flights that reduce the emissions of greenhouse gases and thus the impact on climate.

C.5.9 Questions linked to ClimOP OIs - Flying low and slow

The participants were given a context about the OI "Flying low and slow" and then asked questions about the price they would be willing to spend to support this OI and about the acceptance of longer travel times.

Many aircraft tend to fly at an altitude of above 10 km, where the emissions of greenhouse gases (GHG) 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 on climate change could potentially be reduced by 15 to 20%.

- Q24: 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?
- Q25: 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?

Q24 Short haul

Table 87. Ticket prices increase for flying low on short-haul flights

Ticket short	Frequency	Percentage	Cumulative percentage
Up to 100€	93	22.9	22.9
Up to 125€	129	31.8	54.7
Up to 150€	122	30.0	84.7

Up to 200€	51	12.6	97.3
More than 200€	11	2.7	100.0
Tot	**406**	**100%**	**100%**

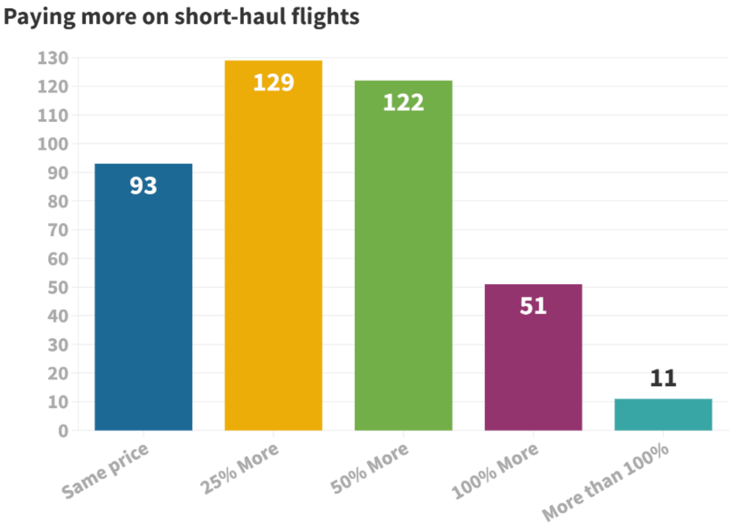


Figure 76. Ticket prices increase for flying low on short-haul flights

About three out of four respondents would be willing to pay a higher ticket price for short-haul flights, knowing that this costs more to the airlines but could also be beneficial to mitigate the climate impact. Specifically, 32% would be willing to pay up to 25% more than the current price, another 30% up to 50% more and about 15% would be prepared to pay double. By contrast, 23% (N=93) of respondents would only pay about the current ticket price or less. These results show a positive attitude on the passengers' side, however the introduction of higher fares should be considered only in connection with policies that mitigate airline additional expenses.

Q25 Long haul

Table 88. Ticket prices increase for flying low on long-haul flights

Ticket long	Frequency	Percentage	Cumulative percentage
Up to 800€	129	31.8	31.8
Up to 1000€	163	40.1	71.9
Up to 1200€	82	20.2	92.1
Up to 1600€	25	6.2	98.3
More than 1600€	7	1.7	100.0
Tot	**406**	**100%**	**100%**

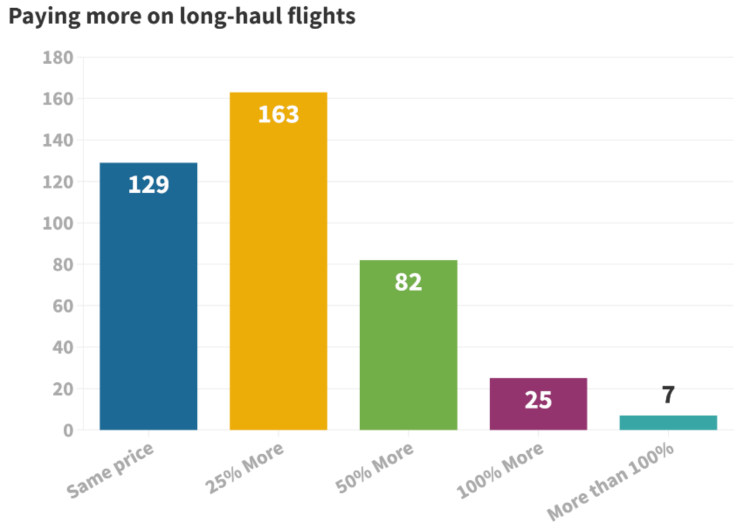


Figure 77. Ticket prices increase for flying low on long-haul flights

With long-flights, which already have rather expensive tickets, a similar distribution is found but there is an increase in the proportion of respondents that would only pay as much as the current tickets (32%, N=129) or up to 25% more (40%, N=163). By contrast, the number of respondents that would be willing to pay 50% or more than the present price is reduced.

Table 89. Statistics of the results of questions Q24 and Q25 on ticket prices

Ticket prices	M	SD	Sum
Short haul	2.40	1.056	976
Long haul	2.06	.959	836

Questions 26 and 27 investigated the acceptance of longer-duration flights, which is one of the consequences of the operational change that would be introduced by “flying low and slow”.

The greenhouse gas emissions (GHG) 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 15% would reduce the climate impact emissions of GHG by 4%. However, this would also increase the duration of the flights.

- Q26: Knowing that this would be beneficial to fight climate change, how much would you be in favour of taking 3 hours instead of 2 hours and 30 minutes, to fly from Rome to London (or similar European flight)?
- Q27: Knowing that this would be beneficial to fight climate change, how much would you be in favour of taking 13 hours 30 minutes instead of 11 hours 40 minutes, for a Paris-San Francisco flight (or similar transoceanic flight)?

When it comes to the timing of flying slower, respondents answer similarly for both short and long flights.

Q26 Short haul

Table 90. Time increases for flying slow on short-haul flights

Ticket long	Frequency	Percentage	Cumulative percentage
Absolutely not in favour	19	4.7	4.7
Not in favour	24	5.9	10.6
Neutral	100	24.6	35.2
In favour	96	23.6	58.9
Absolutely in favour	167	41.1	100.0
Tot	**406**	**100%**	**100%**

A total of 64.7% of participants would be either absolutely in favour (N=167; 41.1%) or in favour (N=96; 23.6%) of increasing the flight duration by 20% on short-haul (30 minutes more on a 2.5h flight). With a mean item answer of M=3.91, SD=1.14.

Q27 Long haul

Table 91. Time increases for flying slow on long-haul flights

Ticket long	Frequency	Percentage	Cumulative percentage
Absolutely not in favour	20	4.9	4.9
Not in favour	26	6.4	11.3
Neutral	112	27.6	38.9
In favour	102	25.1	64.0
Absolutely in favour	146	36.0	100.0
Tot	**406**	**100%**	**100%**

A total of 61.1% of respondents would be either absolutely in favour (N=146; 36%) or in favour (N=102; 25.1%) to increase flight time by 16% on long-haul (almost 2h more on an 11.5h flight). With a mean item answer of M=3.81, SD=1.14.

Table 92. Statistics of the results of Q26 and Q27 about flying slow on short- and long-haul flights

Time	M	SD	Sum
Short haul	3.91	1.144	1586
Long haul	3.81	1.141	1546

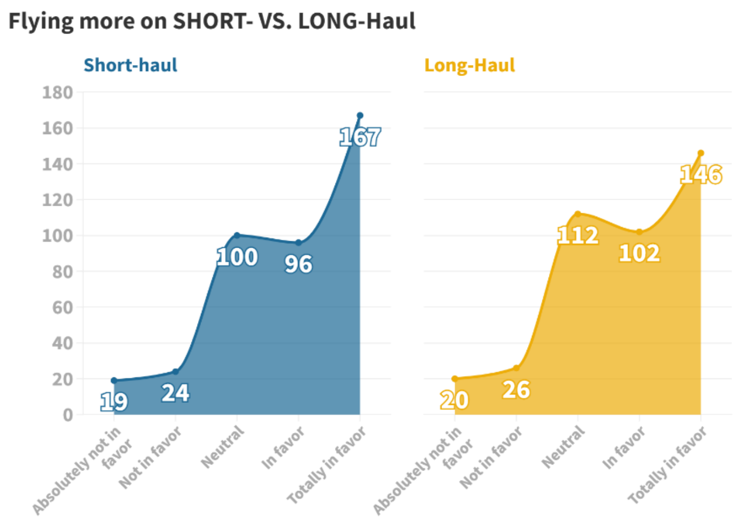


Figure 78. Flying slow on SHORT- vs. LONG-haul flights

C.5.10 Questions linked to ClimOP OIs - Intermediate Stop Over (ISO)

The survey participants were asked the following:

An optimised network of connections between airports can potentially reduce the impact of aviation greenhouse gases emissions on climate by 4-5%. However, this would imply that direct connections could be cancelled and replaced by multi-segment flights.

- Q28: 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?
- Q29: How much would you be in favour of taking segmented flights with longer stopovers to spend some time exploring the intermediate city?

Q28 2-3 segment flights

Table 93. Results of the Q28 on the acceptance of two-to-three segment flights (ISO)

2-3 segments	Frequency	Percentage	Cumulative percentage
Absolutely not in favour	47	11.6	11.6
Not in favour	69	17.0	28.6
Neutral	154	37.9	66.5
In favour	82	20.2	86.7
Absolutely in favour	54	13.3	100.0
Tot	406	100%	100%

Most respondents (almost four out of ten) are neither in favour nor against splitting their (long) flights in two or three segments. The other respondents are almost equally split between those that are not in favour (28.6% in total) and those that in favour of this measure (33.5%) This equilibrium is also shown by the mean and standard deviation of the results: M=3.07, SD=1.17.

Q29 longer stop-overs exploring the city

Table 94. Results of Q29 about the acceptance of longer stop-overs exploring the city (ISO)

Longer stop-overs	Frequency	Percentage	Cumulative percentage
Absolutely not in favour	46	11.3	11.3
Not in favour	50	12.3	23.6
Neutral	134	33.0	56.7
In favour	103	25.4	82.0
Absolutely in favour	73	18.0	100.0
Tot	406	100%	100%

A total of 43.4% of respondents would either be absolutely in favour (N=73; 18%) or in favour (N=103; 25.4%) of taking segmented flights with longer stop-overs to spend some time exploring the intermediate city. As for the previous question, most respondents were neutral (N=134; 33%). Nonetheless, there is a moderate increase of people who are from in favour to absolutely in favour. This highlights the relevance that passengers' benefits (for example exploring two cities at the same ticket price) could have from the introduction of this measure.

Table 95. Statistics of the results of Q28 and Q29 (ISO)

ISO	M	SD	Sum
2/3 segment flights	3.07	1.169	1245
Longer stop-overs	3.26	1.218	1325

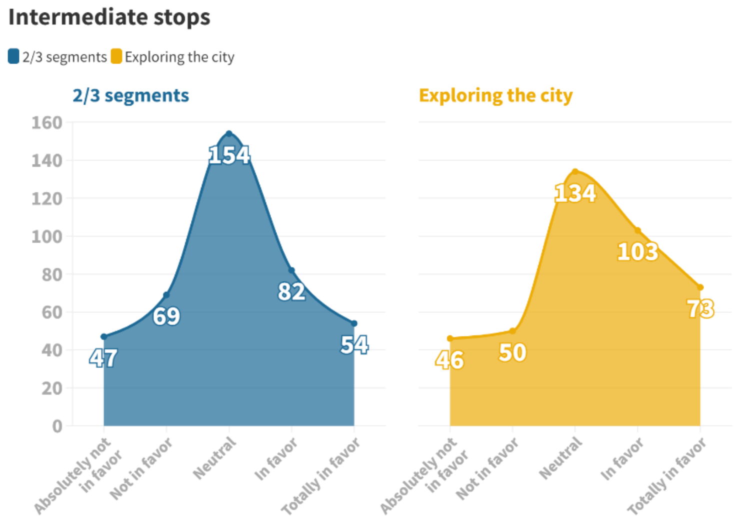


Figure 79. Intermediate stops of 2/3 segments vs. longer stops exploring the city

C.5.11 Questions linked to ClimOP OIs - Network Management and baggage limitations

The rationale of these questions is to investigate whether the survey participants are willing to accept changes to the flight network that try to optimise the number of flights that are necessary to satisfy the current demand of seats from different airport pairs. The trade-off that the respondents are asked to evaluate is to travel on larger aircraft, with less frequent flying options and eventually with restrictions on the luggage weight to maximise the number of passengers allowed on board.

The survey participants were asked the following:

> The aircraft emissions of greenhouse gases are proportional to the weight of the aircraft. If you reduce the weight of an aircraft from Rome to Helsinki by 3500 kg, the greenhouse gases emissions of this flight would be reduced by 5%. This could be achieved by allowing passengers a maximum of 3kg of luggage (i.e. just a small hand baggage).
>
> - Q30: Knowing that this would be beneficial to fight climate change, how much would you agree to baggage limitations?
>
> Reducing the frequency of flights to always guarantee that they are fully loaded and using larger aircraft would help reduce the emissions of greenhouse gases (GHG). For example, if on a busy route such as London – Amsterdam, we could reduce the number of flights from about 10 to 7 flights a day, the number of passengers on each flight would increase by 50%. This would have two advantages: an absolute decrease of GHG emissions because of the fewer flights, and a relative decrease of GHG emissions per passenger by up to 25% because the aircraft fly at full payload.
>
> - Q31: Knowing this, how much would you agree to have less frequent flight connections?
> - Q32: How much would you agree to travel on larger aircraft fully booked?

Q30 Baggage limitations

Table 96. Results of Q30 about the acceptance of baggage limitations

Baggage limitation	Frequency	Percentage	Cumulative percentage
Absolutely not in favour	31	7.7	7.7
Not in favour	61	15.1	22.7
Neutral	126	31.1	53.8
In favour	103	25.4	79.3
Absolutely in favour	84	20.7	100.0
Tot	**405**	**100%**	**100%**

Most respondents were neutral (N=126; 31%), 46% of respondents would be absolutely in favour (N=84) or in favour (N=103), whereas about 23% are against these rather strict limitations to their baggage.

Q31 Less frequent flight connections

Table 97. Results of question Q31 about the acceptance of less frequent flight connections

Less connection	Frequency	Percentage	Cumulative percentage
Absolutely not in favour	11	2.7	2.7
Not in favour	28	6.9	9.6
Neutral	128	31.6	41.2
In favour	119	29.4	70.6
Absolutely in favour	119	29.4	100.0
Tot	**405**	**100%**	**100%**

58.8% respondents are absolutely in favour (N=119) and in favour (N=119) of less frequent flight connections, while 31.6% are neutral (N=128) and only about 10% are against.

Q32 Travel larger aircraft fully booked

Table 98. Results of Q32 about the acceptance of travelling on larger aircrafts fully booked

Larger a/c fully booked	Frequency	Percentage	Cumulative percentage
Absolutely not in favour	13	3.2	3.2
Not in favour	24	5.9	9.1
Neutral	96	23.7	32.8
In favour	107	26.4	59.3
Absolutely in favour	165	40.7	100.0
Tot	**405**	**100%**	**100%**

When coming to travel on larger aircraft fully booked, 66.4% respondents are absolutely in favour (N=107) and in favour (N=165), while 31.6% are neutral (N=96). Once again, aviation passengers show to make decisions based on individual benefits or costs.

Table 99. Statistics of the results of Q30, Q31 and Q32

NETW	M	SD	Sum
Baggage limitation	3.57	1.188	1363
Less connection	3.76	1.037	1522
Larger a/c fully booked	3.96	1.082	1602

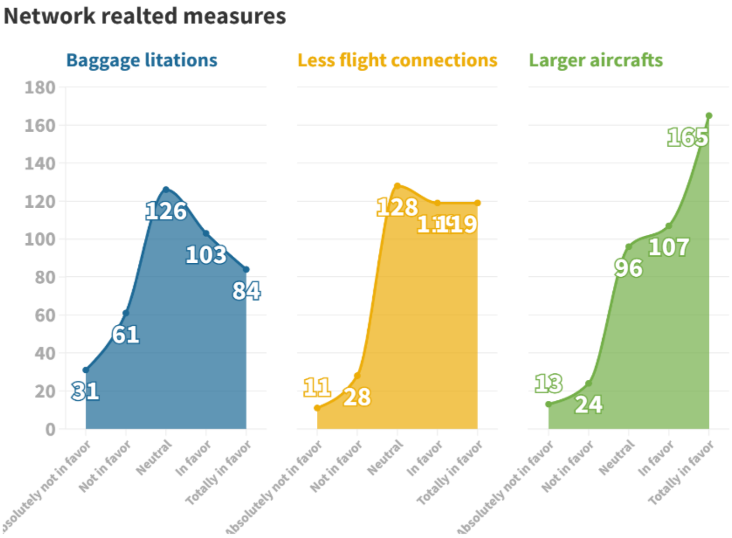


Figure 80. Network related measures

C.5.12 Questions linked to ClimOP OIs - Ground Operational Improvements

This set of questions were proposed to assess the social acceptance of three OIs dealing with more efficient airport Infrastructures (INFR), greener taxiing operations (SETX), and Electric Ground Support Equipment (ELEC).

Participants were asked to express their opinion to the following:

Several airports are currently transitioning to completely electric ground operations, which will cut to almost zero the local greenhouse gases (GHG) emissions from ground vehicles. In addition, these airports are committed to producing and using renewable energy, so that they are effectively climate neutral.

- Q33: How likely is it that you would choose to travel from an airport, if you knew that this airport is climate neutral?

Q33 Climate-neutral airports

Table 100. Results of Q33 about climate-neutral airports

Climate-neutral airports	Frequency	Percentage	Cumulative percentage
Absolutely not in favour	17	4.2	4.2
Not in favour	23	5.7	9.9
Neutral	128	31.6	41.5
In favour	110	27.2	68.6
Absolutely in favour	127	31.4	100.0
Tot	**405**	**100%**	**100%**

When it comes to travel from and to climate-neutral airports, 58.6% of respondents are absolutely in favour (N=127) and in favour (N=110), while 31.6% are neutral (N=128).

Table 101. Mean and standard deviation of the results of the question Q33 about the preference to travel from and to climate neutral airports

Ground OIs	M	SD	Sum
Climate neutral airports	3.76	1.086	1522

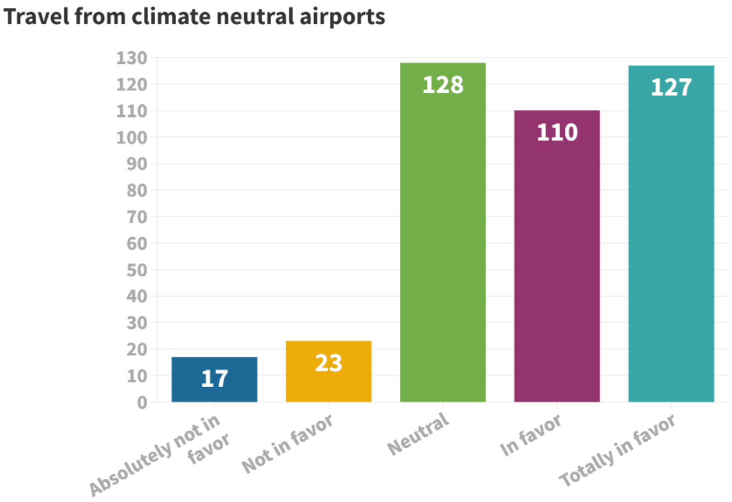


Figure 81. Climate neutral airports

C.5.13 Support to Institutional and social actions

The following items analysed the respondents' disposition towards institutional measures to support greener aviation. In particular, they focus on people's willingness to sign petitions to promote climate-friendly flights and taking flights based on "climate-reputation".

Participants were asked to express their opinion to the following:

- Q34: 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)?
- Q35: If the government would put in place a transparent and objective system to assess the "climate friendliness" of the operations of different aviation companies, how likely is it that you would consider choosing your flights based on the climate reputation?

Q34 Sign petition promote climate friendly flights

Table 102. Results of Q34 about promoting climate-friendly flights

Promote climate friendly flights	Frequency	Percentage	Cumulative percentage
Absolutely not in favour	19	4.7	4.7
Not in favour	17	4.2	8.9
Neutral	107	26.4	35.3
In favour	126	31.1	66.4
Absolutely in favour	136	33.6	100.0
Tot	**405**	**100%**	**100%**

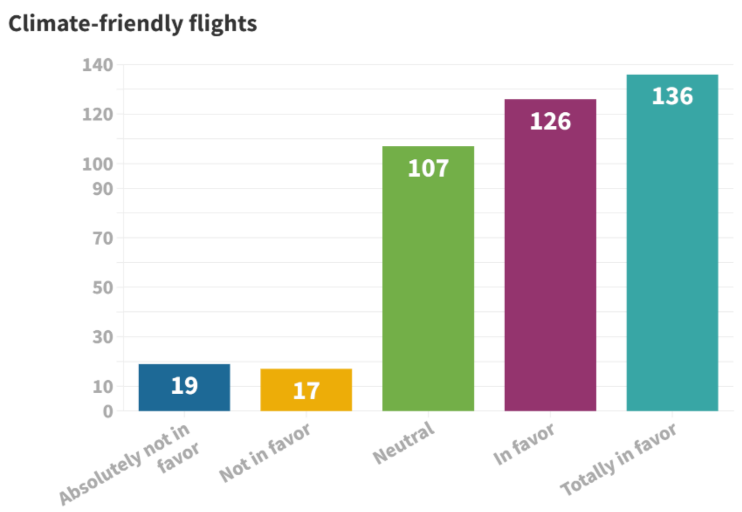


Figure 82. Promote climate-friendly flights

Regarding the political aspects and possible involvement in signing a petition to promote climate-friendly flights, 64.7% of respondents would be absolutely in favour (N=136) and in favour (N=126).

Q35 Flight based on climate reputation

Table 103. Results of Q35 about fliying based on climate reputation

F. climate reputation	Frequency	Percentage	Cumulative percentage
Absolutely not in favour	15	3.7	3.7
Not in favour	18	4.4	8.1
Neutral	100	24.7	32.8
In favour	149	36.8	69.6
Absolutely in favour	123	30.4	100.0
Tot	**405**	**100%**	**100%**

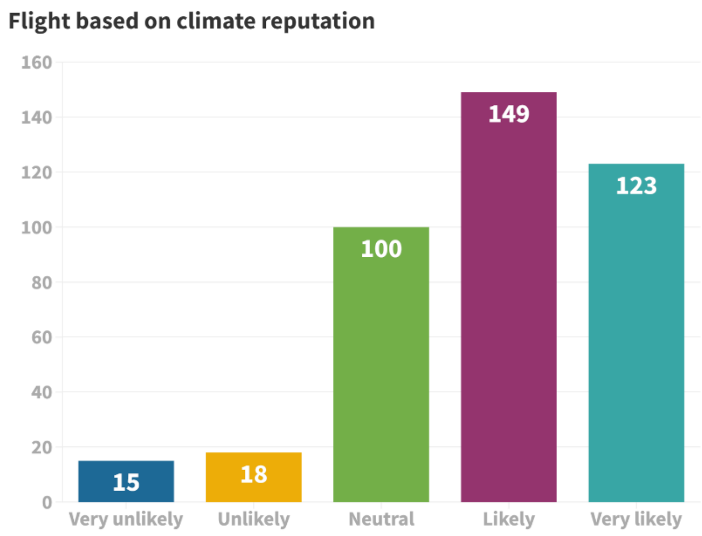


Figure 83. Flight based on climate reputation

And when the political aspect concerns the flight reputation on climate matters, 66.8% of respondents would be absolutely in favour (N=123) and in favour (N=149). Therefore, policies fostering the implementation of the ClimOP operational improvements may be crucial in determining the success of our solutions.

Table 104. Statistics of questions Q34 and Q35

Friendly/reputation	M	SD	Sum
Sign petition	3.85	1.081	1558
F. climate reputation	3.86	1.022	1562

C.5.14 Social Influence

Participants were asked to express their opinion to the following questions:

- Q36: Would you ask for advice before taking a flight which implements operational improvements to mitigate its impact on climate?
- Q37: Would you decide to take a flight which implements operational improvements to mitigate its impact on climate if most of the people you know were doing so?

Q36 Ask for advice before taking a flight that employs OIs

Table 105. Results of Q36 about asking for advice before taking a flight

Ask for advice before taking a flight that employs OIs	Frequency	Percentage	Cumulative percentage
Very unlikely	25	6.2	6.2
Unlikely	48	11.9	18.0
Neutral	135	33.3	51.4
Likely	123	30.4	81.7
Very likely	74	18.3	100.0
Tot	**405**	**100%**	**100%**

Participants when asked to express the likelihood to ask advice before taking a flight with OIs, 48.7% answered that they would be very likely (N=74) or likely (N=123). Again, an important portion of the sample would remain neutral to the question (N=135). These results are in line with the respondents' opinion following which the surrounding people are less aware of climate change compared to how aware they feel to be (Q12).

Q37 Fly with OI if majority of people are doing so

Table 106. Results of Q37 about the Social Influence in taking decisions and actions

Fly OIs if others do	Frequency	Percentage	Cumulative percentage
Very unlikely	17	4.2	4.2
Unlikely	19	4.7	8.9
Neutral	115	28.4	37.3
Likely	144	35.6	72.8
Very likely	110	27.2	100.0
Tot	**405**	**100%**	**100%**

62.8% of respondents answered that they would very likely (N=110) or likely (N=144) fly on a flight which deploys operational improvements if most of the people they know did so. Also in this case, however, a proportion of participants of almost one-third were neutral. It should be also noted that the increase of neutral replies in the last questions could have been influenced by the length of the questionnaire and the complexity of the questions.

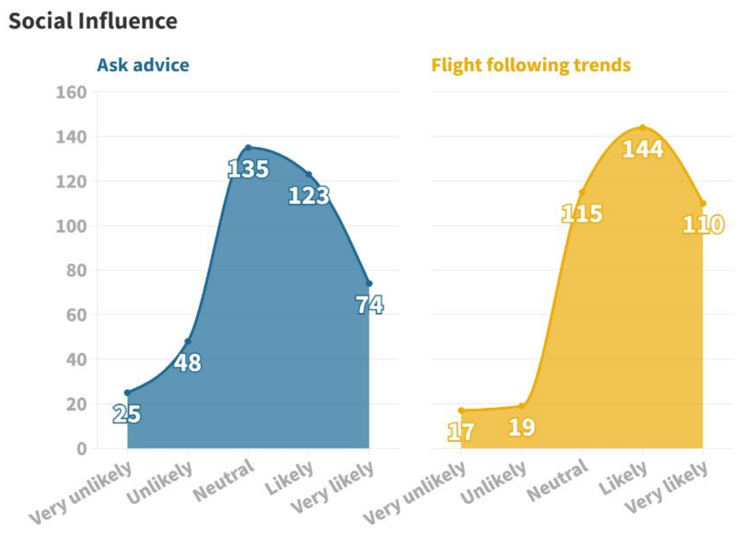


Figure 84. Social influence

C.5.15 Analysis of variance and correlations

MANOVA

A Multivariate analysis of variance (MANOVA) was conducted to identify the factors that play a major role in predicting the social acceptance of ClimOP operational improvements. The results of the Multivariate Test show a significant difference in the answers given by nation and income.

NATION

The results of the Test of Between Subject Effects show that the country of origin has a significant effect on the willingness of people to increase the duration of the short-haul flight ($F_{7,7}=2.56$; $p < 0.05$; η^2 (partial) = 0.068) and the long-haul flight ($F_{7,7}=2.44$; $p < 0.05$; η^2 (partial) = 0.065) to reduce the climate impact emission. Furthermore, the results of the Test of Between Subject Effects show that the country of origin has a significant effect on the willingness of people to travel on larger aircraft fully booked ($F_{7,7}=2.16$; $p < 0.05$; η^2 (partial) = 0.058). To investigate which specific group differed, a post-hoc Tukey Test was performed.

The post-hoc Tukey Test (Table 44) confirms our hypothesis, showing that the answers to the questions differ significantly based on the country of origin at $p<0.01$ for question 26,27 and 32, as shown in the table below.

Table 107. Results of the post-hoc Tukey Tests on Nation by Q26, Q27 and Q32

Dependent Variable	Nation 1	Nation 2	Mean Difference	Std. Error	Sig.
People willingness to increase the duration of a short-/long-haul flights to reduce the climate impact emissions of GHG (Q26/27)	Italy	UK	.93	0.172	p<0.01
		Germany	.97	0.171	p<0.01
		France	.94	0.170	p<0.01
		Spain	.88	0.191	p<0.01
	Netherlands	UK	1.13	0.306	p<0.01
		Germany	1.18	0.306	p<0.01
		France	1.15	0.305	p<0.01
		Spain	1.09	0.317	p=0.01
How much would a person agree to travel on larger aircraft fully booked?	Italy	UK	.62	0.162	p<0.01
		Germany	.94	0.161	p<0.01
		France	.90	0.160	p<0.01
		Spain	.86	0.180	p<0.01
	UK	Germany	.90	0.288	p<0.01
		Italy	-.62	0.162	p<0.01
	Germany	Italy	-.94	0.161	p<0.01
	France	Italy	-.90	0.160	p<0.01

INCOME

The results of the Test of Between Subject Effects show that the income has a significant effect on how much would the people be willing to spend for a long-haul flight that has a lower impact on climate ($F_{3,3}=3.89$; $p < 0.05$; η^2 (partial) = 0.045).

The results of the Test of Between Subject Effects show that the income has a significant effect on how much would the people be in favour of having 2-3 sectors flights instead of direct flights to reach a destination ($F_{3,3}=3.33$; $p < 0.05$; η^2 (partial) = 0.039).

To investigate which specific group differed, a post-hoc Tukey Test was performed.
The results of the post-hoc Tukey Test (Table 45) show that the answers to the question differ significantly based on the income at p<0.01 for Q25, as shown in the table below. In particular, the marginal means in Q25 (Ticket long-haul) is higher for >60.000 when comparing it to <20.000 and 20.000-40.000. In oder words, people who perceive an income above 60.000 € are more likely to pay more a ticket for long-haul flights knowing that is for reducing the impact on climate change.

Table 108. Results of the post-hoc Tukey Test on Income by Q25

Dependent Variable	Income 1	Income 2	Mean Difference	Std. Error	Sig.
How much would a person be willing to spend for a flight that has a lower impact on climate	>60.000 €	< 20.000 €	.51	0.124	p<0.1
		20.000 - 40.000 €	.35	0.114	p<0.1

CORRELATIONS

From the EDA, it emerges that the data are not approximately normally distributed. The normal distribution peaks are, in fact, not in the middle and are not symmetrical about the mean. The Shapiro Wilk's Test confirms those results.

Because the data are not normally distributed, the Spearman Correlation was conducted. All the correlations mentioned below are positively correlated, and there have only been reported medium/high correlations (between 0.56 onwards).

The results show that:

- People who feel climate change as a global issue (Q11) are also those concerned about air pollution (r = 0.672, p< 0.01, two-tailed test) and extreme weather conditions (r = 0.58, p< 0.01, two-tailed test) as an environmental issue (Q10). People who feel climate change as a global issue (Q11) are also those more in favour of taking action to cope with climate change (r = 0.72, p< 0.01, two-tailed test) and **those willing to increase the duration of short-haul flights** (r = 0.59, p< 0.01, two-tailed test).

- There is a significant correlation between the people in favour of taking action to cope with climate change (Q13) and those concerned about air pollution (r = 0.64, p< 0.01, two-tailed test). Those people were also found to believe that the awareness of environmental-responsible behaviours influences the decisions (Q14).

- The people that are aware of any European initiatives to mitigate climate change (Q16) are also those more aware of any initiatives taken at a National level by the Country to mitigate climate change (Q17) (r = 0.59, p< 0.01, two-tailed test).

- There is a correlation between how much the people think is the share of aviation today (Q19) and how much the people think the share is going to be in 2050 (Q20) (r = 0.70, p< 0.01, two-tailed test).

- The people interested in rethinking their mobility toward climate change mitigations (Q22) are also those:
  - thinking that aviation should introduce measures to reduce its climate impact (Q21) (r = 0.58, p< 0.01, two-tailed test)
  - thinking that it would be important to take a flight aimed at reducing emissions of greenhouse gases (Q23) (r = 0.59, p< 0.01, two-tailed test).

- There is a significant correlation (r = 0.71, p< 0.01, two-tailed test) between how much a person would be willing to spend for a short-haul flight and a long-haul flight that travels at lower altitudes, knowing that this has a lower impact on climate. (Q24/Q25)

- The people willing to increase the duration of short-haul flights are also those willing to increase the duration of long-haul flights (r = 0.744, p< 0.01, two-tailed test) to benefit from climate change (Q26/27)

- There is a significant correlation between the people agreeing to travel on larger aircraft fully booked to reduce the frequency of the flights and, therefore, to reduce the emission of GHG (Q32) and those willing to increase the duration of short-haul flights (r = 0.59, p< 0.01, two-tailed test) to benefit from climate change (Q26). People agreeing to take flights that reduce the emission of greenhouse gases (Q23) are also those agreeing to travel on larger aircraft fully booked (r = 0.58, p< 0.01, two-tailed test)

- The people that would be willing to sign a petition to foster regulations that promote flights that are more climate-friendly (Q34) are also those who are considering choosing their flight based on the climate reputation of the airline (r = 0.60, p< 0.01, two-tailed test) (Q35)

C.5.16 Discussion

The survey aimed to evaluate the social acceptance of the operational improvements developed by the ClimOP Consortium during most of its activity. The group of subjects (N=406) was selected randomly across several EU countries in order to have a cluster representative of the European population. Italy (N=84), Germany (N=74), France (N=74), the United Kingdom (N=75), Spain (N=52), and the Netherlands (N=15) are among the countries well represented and which have the larger share of the EU population. Nonetheless, the results produced by the present survey cannot be generalised to the European level because the number of subjects and EU countries collected is limited. Other factors, such as the young age (between 18-44 years, N=291; 71.7%) and high level of education (at least one University diploma, N=249; 61.33%) don't allow us to translate the results from this survey to Europe. The group is normally-distributed for the variable income. As a bottom line, we can consider the present results representative of a specific segment of the EU population.

Concerning their travel habits, the respondents affirmed to employ petrol-powered vehicles as means of transport (N=260; 64%), but a consistent part of them are keen to use sustainable transportation such as buses, bikes and trains (N=125; 30,7%). In relation to the flight frequency before the pandemic, the group can be split into three groups:

- low-frequency travellers (N=149; 36.7%) that fly once a year or less;
- medium frequency travellers (N=145; 35.7%) that fly two to four times per year;
- high-frequency travellers (N=112; 27.6%) travelling once a month or more;

Most respondents perceive climate change as a global issue (N=301; 74%). Environmental pollution (m=3.9), extreme weather conditions (m=3.96) and loss of biodiversity (m=3.81) are the phenomena on which the subjects agreed as environmentally relevant issues. Moreover, when asked to express their opinion on how much they think climate change is an issue for the others, the pattern of replies changes toward lower values. Indeed, only 52.5% of people around the respondents view climate change as an urgent issue.

Even though 69% of respondents are willing to take action to cope with climate change, the majority take between none to one decision to present the environment daily (N=263; 64.8%). This incoherence may be due to the fact that most of them are unaware of mitigation initiatives at any level [74], as shown in Tables 16, 17 and 18. Moreover, only half of them claim that awareness influences climate-friendly behaviours (N=227; 56%).

The awareness about the climate impact of aviation is also low, or perhaps it reflects the influence of public campaigns such as the “Flygskam” or “Flight Shame”. Indeed, only 19.5% of respondents were aware of the actual climate impact of aviation (as shown in Table 19). When asked to foresee the future impact of the aviation domain, the subjects state that this domain will probably compose 10-30% (N=101) or 30-50% (N=107) of the total human impact. Again, the results highlight a scarce awareness, though the increase is in line with the ICAO’s forecasts that the CO_2 emissions from the aviation sector in 2040 will be three times as many as in 2015 [75]. Nonetheless, the subjects slightly agreed on the need for mitigation measures in aviation (N=145; 60.3%), the interest in rethinking their mobility (N=267; 65.8%), and the importance of taking flights that reduce their emissions (N=264; 65%).

When asked to express their opinion on the ClimOP operational improvements, the majority (N=222; 62%) claimed to be keen to pay from 25-50% more for a flight on short-haul as well as for long-haul flights (N=245; 60.3%), knowing that is to mitigate the climate impact of aviation.

A total of 64.7% (N=263) participants would be in favour to increasing flight time by 20% on short-haul (30 minutes more on a 2.5h flight), and a total of 61.1% would accept increasing flight time up by 16% on long haul flights (almost 2h more on an 11.5h flight). Intermediate Stop Over (ISO) is preferred when passengers can benefit from longer stops to explore the city where the flight stops (Figure 25).

Regarding strategic network management (NETW), passengers are keener to have less frequent flight connections (N=278; 58.8%) and to travel with larger aircraft fully booked (N=272; 67.2%) than having baggage limitations (N=187; 46.9%).

When it comes to travel and land in climate-neutral airports, 58.6% of respondents are in favour (N=237), while 31.6% are neutral (N=128). People show to be slightly in favour of traveling from a climate-neutral airport. The slight preference may depend on the low awareness of what climate-neutral airports are.

The majority would be in favour of fostering climate-friendly flights by signing a petition (N=162; 64.7%) and choosing flights based on their “climate reputation” (N=272; 67.2%). Though passengers may not prefer to ask for advice before taking a climate-friendly flight (N=197; 48.7%), they will fly with the ClimOP operational improvements if the majority would do so (N=254; 62.8%).

The MANOVA results show that Nationality is a predictive factor for flying slow and flying with larger aircraft fully booked, while the income predicts how much would the people be willing to spend for a long-haul flight and how much would the people be in favour of having 2-3 sectors flights instead of direct flights.

It should be noted that the replies to the questionnaire may be influenced by social-desirability bias [76]. The effect of this bias consists of the tendency of survey respondents to answer questions in a manner that will be viewed favourably by others.

C.5.17 Conclusions

The results from the aviation passengers survey show that many respondents are willing to act or modify their habits if they know this mitigates the human contribution to climate change. However, this attitude does not necessarily translate into action. The awareness may be a variable influencing their idleness. Most respondents rated ClimOP operational improvements positively. Aware of the changes introduced in the flight experience, the respondents appeared to be keen to pay more for greener flights or increase flight times. These results clarify the passengers' disposition towards the introduction of changes in their flight experience. Passengers resulted to be in favour of rethinking their way to travel in case the impact on them is balanced by some benefit. One example, in the case of intermediate stopovers, is the opportunity to explore new cities during the additional stop introduced in the flight. These results will also be taken into account in WP3 as an indication of the opinions of one (often neglected) stakeholder in aviation, namely the passengers. This input, together with the impact analysis on the other aviation stakeholders, will help shape the lessons learnt ClimOP will present to rule makers to decarbonise the aviation sector.

Appendix D: IATA review on inflight OIs

Disclaimer:
The present Appendix collects the results of the assessment carried out independently by IATA on the potential impacts of the OIs on airspace users mostly. It mainly assesses the business and economic impacts in a qualitative manner. The appendix has been finalized before the final technical and scientific results, presented in this deliverable, became available. IATA's assessment is based on rather restrictive assumptions that correspond to the worst-case scenario of the potential impact on airspace users. Therefore, the results have to be intended as the lower limits on the applicability of the OIs. The ClimOP final results, presented in the previous sections, suggest that the OIs might be deployed in a way that is less impactful for the airspace users, while still maximizing the benefit for climate. For instance, *Flying low and slow* reduces the flight level in a minority of the analysed flights, whereas most of the flights remain at the optimal altitude of above 30,000 ft. The work that will be carried out in WP3 will bridge the gap between climate and stakeholder's needs. WP3 will gather all the information on both the climate and non-climate impacts of the OIs to make recommendations on the optimal incentives, investments, policies and regulations to mitigate the impact on the stakeholders while maintaining the beneficial effects on climate.

D.1 Introduction

ClimOP plans to develop a set of mitigation strategies based on the alternative sets of OIs, and consequently will provide recommendations for targeted stakeholders regarding policy actions and supporting measures to implement the alternative sets of Operational Improvements (OIs).

On the 23rd of November 2021, IATA experts attended to a Consortium meeting that had the objective of presenting the set of defined OIs

During the meeting, IATA experts agreed with the consortium leader, DBL, to carry out a qualitative evaluation of a selection of the OIs, to bring onboard the project the aircraft operator and airspace user perspectives. The analysis, although qualitative, has followed a systematic and methodological approach.

This work will serve to update the 2nd iteration of D1.5, as well as to provide overall consistency to the project environmental KPI's and will represent a starting point for further discussion in the framework of WP3 (incentives, business models, involved regulations, etc.) and future integration in WP4.

Attending the relevance in Safety and Flight Operations, six out of ten OIs have been selected for this analysis:

- Flying low and slow
- Free routing in high-complexity environment/flexible waypoints
- Climate-optimised flight planning
- Wind/weather-optimal dynamical flight planning
- Strategic planning: merge/separate flights; optimal network operations
- Climate-optimised intermediate stop-over

As an overall conclusion, the OIs analysed in this document do not seem to be initiatives aligned with IATA's industry and market positions. Therefore, IATA does not fully endorse the OIs as defined in the documentation of the ClimOP project. The airline business is a highly commercial competitive business. The airlines are forced, for their survival, to strive for the most cost-effective network and flight operations. Any improvement would be welcome, but most of the OIs analysed are not new. The level playfield is also to be considered when addressing potential measures towards EU operators.

Understanding that ClimOP is an R&D project, in the framework of its dissemination and promotion activities, IATA encourages the consortium to convey the message to the EU aviation community that the analysis of these operational improvement is done in an exploratory research study aimed at assessing how is the climate impact of different operational concepts from a pure mathematical and scientific methodological standpoints at the time being, and so that, no economic, social, industrial, and market analysis has been performed at the time of drafting this report.

As a final Annex, IATA presents in section 5 its formal position regarding climate change charges on airport and ANS.

D.2 Operational improvements review

The methodology used for the review of the Operational Improvement has been based on the following approach:

- Benchmarking
  - Literature research
  - Research on formal positions of aviation industry stakeholders
  - Judgmental experts cross-check
- High level analysis, conclusion, and suggestions for each OI, with the following documented structure:
  - Understanding of the OI
  - Identified operational benefits
  - Identified operational challenges
  - Evaluation of impact per KPA[12]
  - Qualitative Impact on Airlines DOCs

12 The KPAs to be checked will be the Single European Sky ones, mandated in the Commission Implementing Regulation (EU) 2019/317, about ANS performance scheme

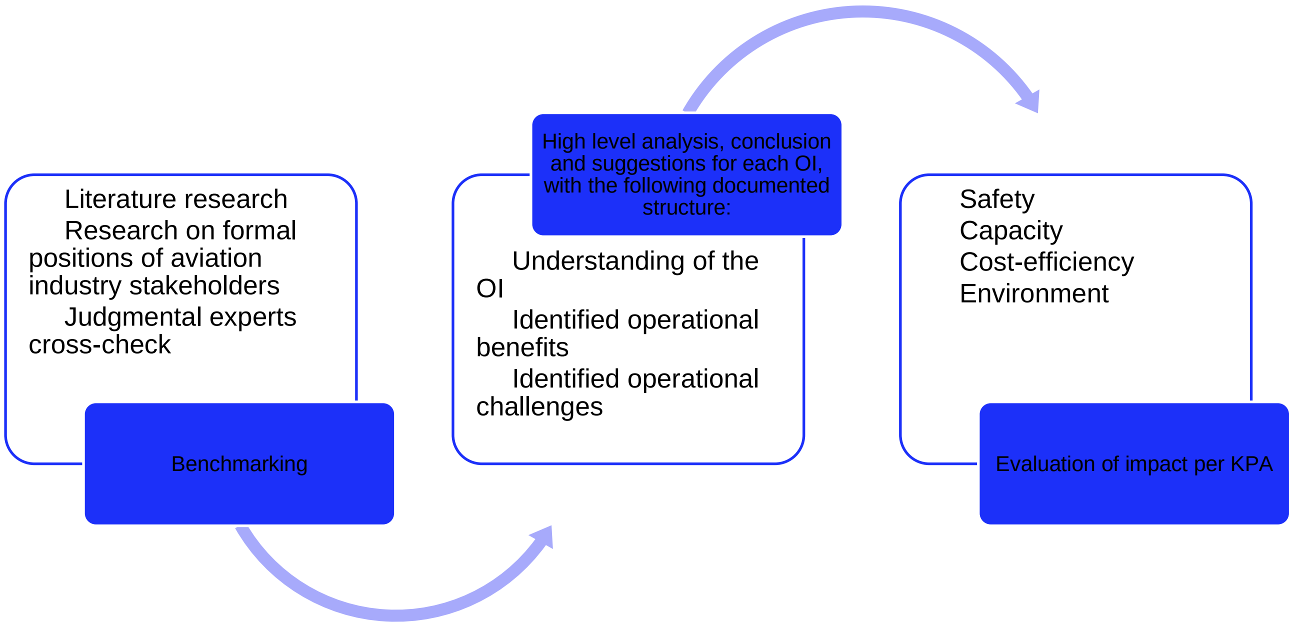


Figure 85. Methodology scheme

D.2.1 Flying low and slow

Understanding of the OI

The basic principle of this OI is to operate the aircraft in low flight levels (level bands not determined yet by the project), with reduced cruise speed (neither defined by the project) to shift the location of cruise emissions down. This would theoretically lead to reduction of non-CO_2 climate effects of the flight, reduction of contrails, and reduction of NO_x and H_2O emissions, but will however increase CO_2 emissions.

According to the ClimOP project documentation, "*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*".

Therefore, the definition and inclusion of this OI pretends to fill an exploratory research gap to assess whether there could be innovations derived from a weather-based comparison of the climate impact of reference flights as flown today, with flights on systematically varied cruise altitudes and speeds.

For this purpose, the project considers developing a Pan-European air traffic scenario (scenario not developed yet) incorporating detailed flight track and profile data, and reproducing real flight trajectory as a baseline, in some selected days with characteristic weather, and future average atmospheric conditions to account for climate change, with a traffic sample of selected days in 2018 and for climate-based study average atmosphere for periods 1991-2020, 2021-2050, and 2051-2080.

Identified operational benefits

After an exhaustive analysis, no operational benefits are identified. See next subsection with complementary information.

Identified operational challenges and evaluation of impact per KPA

The following challenges / limitations / disadvantages have been found for this OI:

- From the aircraft operator perspective:
  - Flying below the optimum cruise FL implies increased fuel consumption and, consequently, additional CO_2 emissions.
    - Fuel overconsumption leads an increase of operating costs
    - Increased CO_2 emissions leads to increased carbon trading charges (CORSIA, ETS). Oceanic flights would not be able to benefit from flying in Jetstream winds, resulting in additional fuel consumption/CO_2 emission.
    - Current turbofan airframes are designed to find optimum FLs above 30.000 feet MSL. Flying lower and outside the optimum bands would represent a non-environmentally friendly operation.
    - A subsequent change of aircraft types / fleet would have a major impact on airlines business models. New models would not be available in sufficient quantities in the medium long term anyway.
  - Slower flights imply longer travels, which would represent direct impact on airlines' business models feasibility. For example (list non-exhaustive):
    - Increased OPEX in terms of flight & cabin crew
    - Longer travels, more time onboard, is an obvious factor for a loss of attractiveness for passengers. This would represent a fall of flight ticket sales, airlines revenues
    - Certain long-haul routes may not be feasible in terms of timing
    - New challenges in terms of crew flight-duty time limitations would arise
- From the airspace user perspective: injecting the same load of traffic in a reduced airspace would imply an overconcentration of traffic in the same airspace volumes, which will affect:
  - Capacity (ATFM delays). It is important to note that before the pandemic, the airlines flying in the EU were already experimenting a capacity crunch [77] in the European ATM Network. Reducing the available airspace will accentuate the problem once the traffic levels are restored.
  - Cost-efficiency: changing the available airspace and the current FL allocations would cause an increase of ATC workload on the ANSP, which would generate a cascading effect of needs for additional ATC staffing. This would lead to an increase of ANS costs / DUC, and therefore an increase of ANS charges for the airspace users (and more expensive tickets for the customers).
  - It is recommended to review the defined set of KPAs and KPIs that the project has established, and to align those with the ones defined in the EU's ANS performance scheme, Commission Implementing Regulation (EU) 2019/317.

D.2.2 Free routing in high-complexity environment/flexible waypoints

Understanding of the OI

The basic principle of this OI is to examine the impact of removing the fixed air traffic service (ATS) routes in high-complexity airspaces. This study will focus on high-density airspaces to expose the impact of this concept for high-complexity workspaces.

This operational improvement is an initiative that, in fact, is being currently deployed by the whole EU-27 member states, mandated by the COMMISSION IMPLEMENTING REGULATION (EU) 2021/116 of 1 February 2021 on the establishment of the Common Project One (commonly known as the CP1), and more specifically, by the ATM functionality AF3, “FLEXIBLE AIRSPACE MANAGEMENT AND FREE ROUTE AIRSPACE”.

Basically, FRA works as a specified airspace in which the users may freely plan a route between defined entry and exit points, subject to airspace availability, with the possibility to choose a route via intermediate, published, or unpublished, waypoints without reference to the ATS route network. Within that airspace, flights remain subject to ATC.

FRA is currently being implemented, in two phases:

- initial FRA: with time and structure constraints.
- final FRA: constant free route implementation with cross-border dimension and connectivity to TMAs.

FRA must be provided and operated in the entire Single European Sky airspace at least above FL305:

- initial FRA by 31 December 2022.
- final FRA, including cross-border FRA with at least one neighbouring state and FRA connectivity with TMAs, by the implementation target date of 31 December 2025.

Identified operational benefits

The operational improvement is, therefore, not a new initiative to be developed and assessed before its adoption, as this is a mandatory ATM functionality that is currently under implementation.

There have been numerous discussions and unsuccessful proposals related to removing airspace boundaries in the Single European Sky (SES) context, all to improve the European airspace utilisation and efficiency. In order to gain any benefits described by the new AF's, it will require a decision to, at a minimum, implement a more efficient upper airspace and implement the SES initiative.

Within the ASM concept, there remain obstacles associated with cross border FRA operations. Primarily, the issue is a result of fixed boundary and communication transfer points. The implementation of FRA, without adapting the existing transfer points, will not provide the benefits expected from User Preferred Routings (UPR) or full trajectory-based operations.

By implementing the promising AAS target, which gives a clear overview of the concepts and changes that will allow building a more optimal and efficient European upper airspace, the benefits related to AMAN/DMAN and ATFM, could be finally achieved. Simply attempting to establish FRA or individual Free Routes, will only lead to marginal or very limited benefits. Under existing procedures, the use of direct routings within a FIR will have the same result as Free Route, absent the implementation and according to the “Transition plan for the operational and technical dimensions of the AAS” and the SES.

There will be a need to synchronise the deployment of airspace management, advanced flexible use of airspace, free route airspace, cross-border free route and FRA connectivity with TMAs, but this must also include ACCs to ensure a wider geographical scope involving many stakeholders. From a technical perspective the implementation of targeted system and procedural changes must be coordinated to ensure that the performance objectives are met.

In addition, FRA concept is erroneously reviewed as an option of flying the shortest Great Circle Distance between two certain points (ideally city pairs). The shortest route does not provide the optimum trajectory in terms of fuel burn and consequently, environmental impact. Existing Flight Planning Tools are suggesting optimum routings considering aircraft performance, payload, weather, charges, and many other factors, the most critical of which is wind direction and velocity. Therefore, the optimum route theoretically should be composed of the direct segments the number, direction, and length of which depends on the various factors with wind factor prevalence.

A the time being, Flight Planning Tool providers offer a limited number of plannable directs, due to system limitations. Flight Planning Tools are not able to provide all possible direct connections. Those Tools do not offer FRA as the optimum solution for AO's. There are some possibilities like: (creation of intermediate points based on ATM published intermediate points + other points which are created in a cooperation between AO's and flight plan providers (for instance fuel check points which are mandatory for Crew). More available points provide better efficiency. However, this cannot be done manually for the longer perspective.

Due to FRA implementation in Europe, Eurocontrol has created a lot of sophisticated TFR (Traffic Flow Restriction) rules which are affecting Flight Planning Systems (much longer calculation time of single OFP).

Because of additional restrictions (vertical limits of FRA airspaces, TFRs, FUA airspace activated by AUP/UUP) occasionally flight dispatchers have difficulties to find any acknowledged by CFMU route.

Lack of modern Flight Planning Tools and airspace complexity are the main factors limiting FRA usage in Europe.

IATA recommends to the consortium members to consider the above explained factors, and to define and develop the simulation scenarios in accordance with the regulated conditions defined in the CP1 implementing rule (airspace > FL305, enroute, and considering initial and final FRA models, and to address Flight Planning Providers with upgrade of Flight Planning Tools to ensure compatibility with FRA operations

Identified operational challenges and evaluation of impact per KPA

It is considered that the evaluation of the FRA concept, mandatory ATM functionality included in the CP1 regulation, does not bring innovative value for the project. Having said this, in terms of KPIs, it can be stated the following:

- Capacity: the fact of the low implementation status and maturity that the EATMN has about the impact of the FRA is still unknown. It is not even discarded the correlation between the doubling of ATFM delay minutes from 2017 to 2018, and the widespread introduction of FRA.
- Environment: more direct routes would theoretically decrease the emissions, but the performance of the system, in terms of reduction of additional miles flown vs the reference trajectory thanks to FRA, is not available yet at the PRB.
- Safety: no relevant aspects to be commented on.
- Cost-efficiency: no relevant aspects to be commented on.

D.2.3 Climate-optimised flight planning

Understanding of the OI

The basic principle of this OI is the implementation of operational measures (neither fully explained, not fully found in the project documentation) that aim to avoid atmospheric regions that are particularly sensitive to non-CO_2 aviation effects, e.g., where persistent contrails form, by identifying alternative trajectories avoiding regions in the atmosphere strongly sensitive to aviation emissions with regards to climate impact.

The overall concept relies on a multi-dimensional environmental change function concept (not available for the current assessment), which is theoretically capable of providing climate impact information to air traffic management (ATM) and airspace users in the strategic / planning phases, to avoid flying in these regions.

The project documentation mentions that with this concept, some flights would require larger deviations from the fuel and cost optimum trajectory and thus create higher operating cost penalties and increased CO_2 emissions. In contrast, for other flights only minor deviations are needed, e.g., when ice super-saturated regions need to be avoided in order not to support contrail formation. Those layers are typically relatively thin and can be avoided by small altitude changes.

Identified operational benefits

The project documentation explains that the modelling chain on climate-optimised flight planning relies on the provision of spatially and temporally information related to the sensitivity of the atmosphere to aviation emissions (regions to be avoided by air traffic).

Considering these climate impact areas, information in the overall objective of the trajectory optimization would theoretically help the system to identify alternative trajectories which have a lower climate impact.

The project expects that the benefits of this pre-selection of promising weather conditions would represent a positive climate impact in terms of reduction of nitrogen oxides (effects on ozone production and methane depletion), water vapour, and contrail cirrus.

However, from the operational point of view, no operational benefit is identified, just challenges (see next subsection).

Identified operational challenges and evaluation of impact per KPA

The following limitations have been found for this OI:

- This OI requires, for the selected weather situation, comprehensive (spatially and temporally resolved) information on the climate impact of aviation emissions (at a given location):
    - Provision of such data requires an analysis of the associated uncertainties and how to consider them adequately in the overall performance assessment.
    - The methodological models are not yet mature enough to assess objectively and quantitatively the impact in terms of costs and benefits for the airspace users.
- Current estimates of the project state that for only small changes in aircraft routing in the North-Atlantic airspace, a climate impact reduction of 10% was possible with a 1% increase in operating cost (mainly fuel):
    - Considering the low maturity of the concept, it is recommended to maintain these estimates as early hypotheses, as a 1% of extra burn fuel represents a considerably high increase of costs and emissions.
    - Longer distances to be flown could be going in the opposite direction of the targets of the ClimOP project as well as in opposite direction to the main drivers of the airline industry.
- It is understood that this OI will not require, for the airspace users, the implementation/installation of additional equipment, either onboard or on the ground segment. However, new flight dispatching working methods and procedures and possibly system upgrades would have to be implemented in the airlines OCCs to consider the potential constraints that represent not to fly in/out to avoid the sensitive areas, which would be an increase of OPEX for the airspace users, as systems would have to be modified/upgraded accordingly.
- As expressed in the chapter about “Flying low and slow”, new constraints and restrictions in the airspace goes against capacity optimization, as reducing the available airspace will accentuate the capacity crunch problem once the traffic levels are restored.
- Additionally, increasing flight times, and/or not flying the preferred flight levels, would worsen the performance of the European ATM Network, making it not feasible for certain States to meet environmental targets imposed by the SES performance scheme.

D.2.4. Wind/weather-optimal dynamical flight planning

Understanding of the OI

Wind/weather-optimal dynamical flight planning concept aims at optimising flight trajectory by considering the available wind and weather information to minimise the negative impact of the MET conditions on the operation. The concept relies on Dynamical flight planning performed in a tactical time scale based on a wind/weather forecast fixed for a six-hour period, for en-route airspaces.

This OI aims is defined to optimise flight trajectory by considering the available wind/weather information to minimise the negative impact on the operation, for reducing flight duration, fuel consumption, whilst releasing less emissions by optimising the trajectory to benefit from using such MET information.

It also considers the evaluation of the relative humidity and environmental temperatures during the optimization process to avoid potential contrail formation areas (to mitigate the green-house effect of contrails).

Identified operational benefits

New operational measures towards fuel consumption reduction are always welcome by the airline industry. However, with the information available it is not possible to provide a deeper assessment to state to what extent the implementation and adoption of new wind-related inputs for the flight planning tactical phases will have any positive or negative effect. IATA looks forward to the analytical and qualitative results of the simulation exercises to be carried out by the ClimOP consortium.

Identified operational challenges and evaluation of impact per KPA

Based on the lack of technical and operational details related to this OI, it is not possible to provide a deep assessment about the potential disadvantages that could bring the implementation of this solution. There is not much detail on how/where/when the information would be integrated, as well as the applicable systems and SOPS to implement such practices, in comparison with the current MET provision for en-route navigation. Nevertheless, and although a qualitative analysis per KPI is not possible with the information available, the following considerations can be provided:

- Currently, FPL systems are loaded at 30min intervals with new weather information and data, including winds, pressure, etc. Flight planning parameters are based on the full-time window for operation, e.g., North long-haul operations will use weather information for the entire flight (up to 12 hours) and the crews will update through the FMS en route. For short-haul operations a 6-hour window would also be fully considered in current methodologies. The operational flight plan is based on performance, weight and MET data to derive the optimal route and level. In an OCC , the airline is dealing with hundreds of flights a day, so wouldn't be able to plan if the system didn't already look "ahead". This concept is not, anyway, new.
- With regard to the impacted stakeholders, the ClimOP project documentation is mainly focusing on the impact on the ATC workload, whereas the impact should be identified beyond the ATS provision. Other functions such as data integration in the EATMN network, in the OCCs, and in the ACCs should be taken into consideration.
- The repercussion of new provision of data and aeronautical information by MET ANSPs should be considered. The feasibility of MET providers delivering dynamic accurate wind data and information, faster than the one delivered nowadays in accordance with ICAO Annex 3 – Chapter 3 (WAFS), is an aspect that should be checked in the framework of this project.
- The MET information to be considered for a tactical and dynamic planning should also be complementary to the one that the aircraft can deliver through observations broadcasted by data link, and therefore it should be deeply analysed from this perspective as well, without well as with the one that data service providers as SITA can deliver in-flight.

- The additional cost for the MET service and for SITA type messaging must also be a consideration.

Finally, as a summary of IATA's view of this OI, with the partial information available at this stage, it may be concluded that an additional effort for documenting the solution with lower level of granularity is needed to provide a deeper assessment.

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

Understanding of the OI

In this OI, the project researches the "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" (as in any other commercial operation/through optimising the network structure, assuming airline's minimum target values in terms of atmosphere Average Temperature Response (ATR) reduction and "operations profitability".

The OI aims at incorporating climate effects associated with route development decisions and re-plan the airlines' networks to reduce ATR, through finding a tailor-made trade-off (balance criteria not provided) between the operational profit and ATR contribution when operating a network based on different airline business models.

According to the project documentation, planning a network by an airline is mainly driven by the estimated demand between considered city pairs. The project will use a commercial database used to obtain the history passenger demand for itineraries and airfares.

According to the project documentation, it is needed to follow three sequential steps to carry out the modelling and analysis of this OI:

- Climate: generating city-pairs to assess the climate impact of various trajectories for each Origin/Destination (OD) under multiple variables: costs, flight times, and aircraft types
- Airline: the model will be executed for four types of representative airlines (Major H&S (Legacy), Secondary H&S, LCC, Regional) while passing on a certain number of alternative trajectories for each OD pair. The result of KPIs for each airline type is then extrapolated to meet the initial air traffic scenario scale.
- Airport: considering the average frequencies for all airports are then delivered to the airport network model to calculate airport related KPIs.

Identified operational benefits

The project pretends with this OI, for the first time, to consider the climate impact of flights at the strategic level, in the route planning layer, by introducing climate impact goals to the network cost-efficiency targets. However, and aligned with the considerations expressed in the next subsection, no operational benefits are identified.

Identified operational challenges and evaluation of impact per KPA

With the information contained in the different documents consulted for the analysis of this OI, it is hardly possible to derive specific and straight-to-the-point conclusions about this theoretical idea. There is missing information about how / where / by whom these measures would be implemented.

Aspects as potential mandates, authorizations, supervision, information sharing, compensations, penalties, faring, market, etc. are not mentioned. The documentation of the project focuses mainly on the scientific side of the evaluation of introducing climate impact related criteria for the determination of the strategic planning of the routes to be operated by, mainly, airlines.

Considering the lack of socio – economic aspects, as well as the lack of details about the implementation of such supposed improvement, it is necessary to mention, at the highest level, that the determination of the route planning for each airline is basically a strategic outcome of a complex business model, owned by the operator in the free States of the EU.

The routes freely determined are specific and unique for each airline operating in each scenario/market segment. In the route planning process, the operators must consider the most appropriate solutions to satisfy their strategy goals, their market demand, business drivers, regulatory, safety and environmental requirements, and a large set of boundary conditions that reduces the degrees of freedom for the operators.

The OPS support functions of an airline are constantly checking and doing route studies for the commercial department, this is fully inclusive of seasonal weather considerations, fuel burn required, based on Time/Cost/Fuel, as well as any other operational aspects that need to be considered. To say that Airlines base the decisions on just the load factor is inaccurate and incomplete.

A theoretical solution that could impose incentives and penalties for using a climate change-driven network of city pairs is against the main drivers and principles of the airline's operation, it could be against the freedoms of a liberalised business and complicates even much more an operational market that before the pandemic, was already stressed in terms of capacity and cost-efficiency performances.

Therefore, the application of monetary constraints linked to the cost-efficiency of the city pairs to be flown, or potential fees or penalties for exploiting routes, will be a measure that theoretically, will not be welcome by the airlines industry.

A hypothetical implementation of such a solution could be done locally, not at an EU network level, and considering a careful stakeholder consultation process to collect all the factors that could potentially represent a severe impact on the aircraft operators, and extensively, on the European Union citizens.

It is even likely that in the pursuit of a climate impact reduction, the indicators in other KPAs could be deteriorated, which at the same time could represent an adverse environmental effect in comparison with the initial goals.

It is suggested, to complement these statements, please refer to section 5, where IATA's position with regard to climate change charges is detailed.

D.2.6 Climate-optimised intermediate stop-over

Understanding of the OI

According to the project documentation, the Intermediate Stop Operations / ISO[13] are intended to help aircraft operators to reduce long-haul nonstop fuel burning by reducing the effort of carrying less fuel during the take-offs. Instead of performing a direct long-haul flight, the project proposes an interrupted mission with an intermediate landing for refuelling. According to the project documentation, the "less fuel has to be carried, weight and thus fuel consumption can be reduced".

While the fuel-saving potential of this concept has been confirmed in previous studies cited by the project, the focus of this study in ClimOP is the evaluation of the climate impact reduction thanks to this operational concept. In addition, and according to the project documentation, fuel-optimised ISO typically leads to higher flight altitudes due to reduced weight and thus, emissions are emitted in more climate-sensitive areas and lead to higher climate impact. Based on this rationale, the project also proposes an additional limitation of flight altitudes to reduce climate impact is an additional aspect of this study. Additionally, the highest fuel consumption and CO_2 emission is generated during

[13] The Project uses, for this OI, the acronym ISO, which perhaps is not fortunate as may be confused with other pre-existing acronyms with the same three letters.

take-off, climb and landing; therefore, by adding an intermediate landing, the savings achieved by decreased consumption in the en-route phase, would be more than negatively offset by the additional take-off and climb.

The scope of this OI is delimited at flights with a great circle distance above 2500 NM. Shorter haul flights are ignored, because the project considers that the application of ISO is only useful for longer hauls.

Based on this factor, an additional aspect of this study is the consideration of a replacement of the long-range aircraft used for the direct flights by aircraft optimized for shorter distances in the ISO missions. In this context, multiple aircraft will be used to ensure that the same number of passengers can be covered.

Identified operational benefits

No operational benefits are found by IATA in the concept of interrupting transoceanic and long-haul flights. See next section related to the challenges and impact per KPA

Identified operational challenges and evaluation of impact per KPA

The operational reality of Aviation today, particularly for long-haul flights, comes from a long history of humankind's efforts and collaboration, towards the achievement of the highest possible levels of safety, whilst at the same time, optimization of the flight times, fuel consumption, and other flight performance parameters, to bring back to societies a continuous positive return for the making possible to exert the business of freedom, flying.

The Intermediate Stop Over, or ISO as recurring concept in this project, is a concept that, if it were feasible, profitable, and effective, would have been implemented. In fact, the aviation market abandoned this operational practice decades ago, when the first aircraft capable of crossing the Atlantic were built, just to avoid, precisely, the stopover.

There are many factors that justify the reasons why IATA rejects this operational concept for alleviating the climate impact of aviation. In order to bring the most important reasons, factors, causes, etc. the information will be provided in two categories: from the aircraft operator standpoint, and from the airspace user one.

- From the aircraft operator perspective:
    - In terms of costs, an intermediate stop-over, an additional jump to bring passengers and cargo from A to B, when previously was performed with direct flights, would imply the following effects (assuming that the number of fuel gallons will be less for flying from A to B with an intermediate stop-over, which might not be realistic due to the facts listed hereunder):
        - It is envisaged an increased costs related to wide bodies decommissioning, as well as increased costs of acquisition of a larger number of aircraft to accommodate the same passenger demands.
        - Increased operational times that imply increased operating costs of flight and cabin crews.
        - Increased costs on maintenance turnarounds, as the airframes will be subject to excessive number of jumps.
        - Increased cost on insurance.
        - Decreased number of passengers due to lack of attractiveness of including one stop to a flight that was done directly in the past.
        - Increased costs of airport fees, as an additional airport should be used in comparison.
        - Increased costs on ANS charges: new hubs airport hubs for intermediate refuelling will have to be served with appropriate and more sophisticated airspace infrastructures than the one used in oceanic and remote continental

en route. Typically, a CTA or TMA should be put in the middle of the Atlantic (the current evaluation will not enter in whether this is feasible) and this would increase the air navigation charges.

        - Increased CO_2 emissions lead to increased carbon trading charges (CORSIA, ETS). Flights in NAT and EUR-SAM corridors would not be able to benefit from flying in Jetstream winds.
        - Current turbofan airframes are designed to find optimum FLs above 30.000 feet MSL. Flying outside the optimum bands would represent a non-environmentally friendly operation.
    - Changing the fleet of an airline by only one specific aircraft type, is an initiative itself that responds to a process in which participate more variables and parameters than the climate impact reduction ones. Therefore, changing the whole EU transoceanic fleet for an uncertain concept like the ISO, is something that does not look feasible and realistic. Hence, the horizon for changing the long-haul fleet should be put at the longest term, as would be a very slow process. This horizon should be compatible with the ones utilised.
    - As expressed in the "Fly Low and Slow" analysis (see section 1.5.3), flying outside the optimum cruise FL bands implies a non-optimized fuel consumption performance, and perhaps, as a consequence, additional emissions: the opposite effect to the pursued one.
    - This OI, like others in this ClimOP project, implies a paradigm change for aircraft operation, and therefore there will be a regulatory and standardization change that will represent a big socio-economic impact for the aviation community.
- From the airspace user perspective:
    - Capacity (ATFM delays): as mentioned in the fly low and slow OI, the ISO mentions that the project proposes a limitation of flight altitudes to reduce climate impact is an additional aspect of this study injecting the same load of traffic in a reduced airspace would imply an overconcentration of traffic in the same airspace volumes, It is important to note that before the pandemic, the airlines flying in the EU were already experimenting a capacity crunch [78] in the European ATM Network. Reducing the available airspace in EUR-NAT and EUR-SAM corridors will accentuate the problem once the traffic levels are restored.
    - Cost-efficiency: changing the available airspace and the current FL, as well as "inserting" a compulsory TMA in between the route would cause an increase of in terms of ANS provision costs, which would generate a cascading effect of needs for additional ATC staffing, which would lead to an increase of ANS costs / DUC, and therefore an increase of ANS charges for the airspace users (and more expensive tickets for the customers).
    - Environment:
        - The project assumes that the intermediate stopover will not imply flying more miles. But this assumption should be challenged, as entering a TMA / CTA for landing in an airport to refuel, implies as a minimum, flying an additional standard arrival (STAR) and an instrumental approach (IAP) before landing, as well as a standard departure (SID) once refuelled. These instrument flight procedures are not usually straight-in flight paths, and so that will increase the distance flown, with an overall result of more fuel burnt, opposite effect to the pursued one.
        - Being realistic, there would be a very limited number of airports to stopover for oceanic flights capable of allocating all ETOPS aircraft types. And these airports, in case they exist, would be probably continuously congested if we maintain the same volume of traffic. Perhaps, the flights would have to deviate

considerably from the orthodromic project of the route, which could be also a handicap in terms of fuel efficiency.

    - The flights could even experience longer distances due to holdings, ATC vectoring, tactical 360's requested by ATC, go-arounds, missed approaches, MET events, and many other events that happen in the vicinity of an airport during ARR/DEP normal operations.
    - Refuelling in a remotely located airport, would imply a landing itself, and as per ICAO rules, alternate airports should be available. The impact of expanding already existing airports, and building new ones, also bring an environmental impact that should be somehow accounted for by the project.
- Safety:
    - the fact of adding one stopover per oceanic and long-haul continental routes, implies to perform two times the number of landings and take-offs. Not pretending to provide a preliminary safety case of this OI, we can firmly state that unnecessary doubling the number of landings and take-offs would increase in more than two-times the inherent levels of risks associated with the normal operations.
    - From the passenger point of view: as of today, flying from Europe to Australia takes about one full day, just short of 24 hours in the fastest way, with one stop. If we need to do three or more stops, the length will become much longer and unbearable.

D.2.7. High-level qualitative assessment of OIs impact on airlines' DOCs

This section summarises a high-level impact assessment of the selected OIs on the direct operating costs of airlines.

The DOCs structure followed is based on IATA's ACGM program (https://www.iata.org/en/programs/workgroups/airline-cost-mgmt/) guidelines and ICAO working material related to airline operating costs and productivity guidelines. IATA's GADM is the data exchange program open to all airlines interested in sharing best practices on airline cost management that foster airlines' financial health, through cost efficiencies and foster sustainable practices. ACMG counts with the active support and participation from over 50 airlines worldwide, which at the same time, represent the best industry source for accurate benchmarking with unique granularity.

The following table includes the qualitative impacts per OI.

Table 109. Qualitative impacts per OI.

	Cost & Operational Data	UoD	Affected by OI? (Yes/No/ TBC)	Foreseen impact (+ / -)	Comments
Flying low and slow	Flight Deck Crew	BH	Y	-	many reasons why this has a strong negative impact, see IATA report
	Fuel and Oil	kg	Y	-	idem previous

	Flight Equipment Insurance	BH	Y	-	worst aircraft utilization which reduces economies of scale and fixed unit costs are higher
	Aircraft Ownership	BH	Y	-	worst aircraft utilisation which reduces economies of scale and fixed unit costs are higher
	Air Navigation Charges	BH	Y	-	reduced capacity increases ATM complexity, accentuate ATSP costs
	Maintenance and Overhaul	BH / FH / Cycle / km	Y	-	engines flying out of optimum FLs
	Airport Charges	Cycle	Y	+	If WB aircraft is replaced by NB, then 2 NB operation could be cheaper than 1 WB operation (generally speaking; it can be different by region). Otherwise, there would be no impact
	Station and Ground	Cycle	Y	+	If WB aircraft is replaced by NB, then 2 NB operation could be cheaper than 1 WB operation (generally speaking; it can be different by region). Otherwise, there would be no impact
Free routing in high-complexity environment /flexible waypoints	Flight Deck Crew	BH	Y	+	Better resources productivity if they can fly more with the saving in time
	Fuel and Oil	kg	Y	+	good expectations from the ANSP community, to

					checked with OI leader and DFS (German ANSP) in Karlsrhue FIR
	Flight Equipment Insurance	BH	Y	+	better aircraft utilization which improves economies of scale and fixed unit costs are lower if more trips during the day can be accommodated
	Aircraft Ownership	BH	Y	+	better aircraft utilization which improves economies of scale and fixed unit costs are lower if more trips during the day can be accommodated
	Air Navigation Charges	BH	Y	-	Full FRA implementation by 2025 will imply ANS charges increase
	Maintenance and Overhaul	BH / FH / Cycle / km	TBC		Fixed part of the cost is diluted due to better utilization but variable part of the cost increases at the same time
	Airport Charges	Cycle	N		
	Station and Ground	Cycle	N		
Climate-optimized flight planning	Flight Deck Crew	BH	Y	-	If flying time increases, then aircraft utilization and crew productivity worsens
	Fuel and Oil	kg	Y	-	Stated in the project documentation
	Flight Equipment Insurance	BH	Y	-	worst aircraft utilization which reduces economies

					of scale and fixed unit costs are higher
	Aircraft Ownership	BH	Y	-	worst aircraft utilization which reduces economies of scale and fixed unit costs are higher
	Air Navigation Charges	BH	Y	-	ANS charges increase due to increase in ANSMET provision costs, and reduced capacity will accentuate ATSP costs
	Maintenance and Overhaul	BH / FH / Cycle / km	Y	-	Variable part of the cost increases because of increased flying time for the same route
	Airport Charges	Cycle	N		
	Station and Ground	Cycle	Y	-	OCCs, flight planning and dispatching: upgrades required on systems / procedures / training
Wind/weather-optimal dynamical flight planning	Flight Deck Crew	BH	TBC		Subject to improving or deteriorating the flying time and therefore the productivity of resources and associated costs
	Fuel and Oil	kg	TBC		Subject to improving or deteriorating the flying time and therefore the fuel consumption
	Flight Equipment Insurance	BH	TBC		Subject to improving or deteriorating the flying time and therefore the productivity of resources and associated costs

	Aircraft Ownership	BH	TBC		Subject to improving or deteriorating the flying time and therefore the productivity of resources and associated costs
	Air Navigation Charges	BH	Y	-	ANS charges increase due to increase in ANSMET provision costs
	Maintenance and Overhaul	BH / FH / Cycle / km	TBC		Subject to improving or deteriorating the flying time and therefore the productivity of resources and associated costs
	Airport Charges	Cycle	N		
	Station and Ground	Cycle	Y	-	OCCs, flight planning and dispatching: upgrades required on systems / procedures / training
Strategic planning: merge/separate flights; optimal network operations	Flight Deck Crew	BH	TBC		Not able to assess impact
	Fuel and Oil	kg	Y	-	See IATA report with the consecuences of implementing such concept of operation
	Flight Equipment Insurance	BH	TBC		Impossible to assess impact
	Aircraft Ownership	BH	TBC		
	Air Navigation Charges	BH	TBC		
	Maintenance and Overhaul	BH / FH / Cycle / km	TBC		
	Airport Charges	Cycle	TBC		

	Station and Ground	Cycle	TBC		
Climate-optimized intermediate stop-over	Flight Deck Crew	BH	Y	-	See IATA report with the consecutives of implementing such concept of operation
	Fuel and Oil	kg	Y	-	
	Flight Equipment Insurance	BH	Y	-	
	Aircraft Ownership	BH	Y	-	worst aircraft utilization which reduces economies of scale and fixed unit costs are higher
	Air Navigation Charges	BH	Y	-	See IATA report with the consecutives of implementing such concept of operation
	Maintenance and Overhaul	BH / FH / Cycle / km	Y	-	
	Airport Charges	Cycle	Y	-	
	Station and Ground	Cycle	Y	-	

+ **means POSITIVE impact, GOOD for the airlines**

- **means NEGATIVE impact, BAD for the airlines**

D.3 IATA position related to climate change charges

Airlines have been investing in newer and quieter aircraft for decades: each new generation of aircraft is on average 20% more fuel-efficient than the model it replaces. However, despite the efforts of the industry, the introduction of new concepts of operation like the ones defined in this project could bring an opposite effect with new charges for the aircraft operators / airspace users, undermining the progress achieved to establish a coherent and effective policy framework to address aviation's impact on climate change.

While the charges that may be applied to an aircraft are considered by airlines as part of their fleet planning, they are just one of many factors such as the performance of the aircraft, marketing, infrastructure, and the economics of operating a specific aircraft type to a specific airport.

Airports

To the extent that the defined OIs may affect airport charges for environmental purposes, internationally agreed policy dictates that this only be directly related to the provision of specific infrastructure or services.

In assessing cost-relatedness, it is important to underline that only actual costs borne by the airport are to be included. These could include costs associated with the provision of new lower-emissions airport ground equipment but should not include external societal costs. As with any investment, projects aimed at reducing the airport's own carbon footprint should be appropriately justified through a capex consultation process.

There are examples of common aircraft types which were designed to meet noise regimes at airports, with the modifications leading to a significant fuel penalty and higher CO_2 emissions. Some noise-reduction measures in engines also lead to higher NO_x emissions, while technologies to reduce NO_x can increase non-volatile particulate matter. It is therefore important that the operational improvements only seek to address environmental impacts at a specific scenario in question.

ANSP charges

While optimising ANSPs services can provide measurable environmental benefits, the same concrete outcome cannot be achieved through the OIs analysed in this report, as we have stated how some of them may increase the ANSP provision costs and therefore, the ANS charges. We have already experienced how ANSP charges in relation to CO_2 emissions SAF may provide a perverse incentive for aircraft operators to fly longer routings to avoid more costly charging schemes.

Also, the ClimOP project should also consider the fact that many airlines are already financially penalised by the lack of optimised ANSP services, creating an increase in fuel burn and compliance costs associated with the resulting emissions (e.g., CORSIA, EU ETS).

It could also happen that the defined OI originate levies intended to recover costs for investments in technologies and solutions that are environment related, and such cost recovery should be cost-related and part of routine capex consultation processes.

The Operational Improvements should be therefore guided by international policies and regulatory requirements.

IATA and its member airlines welcome continued collaboration with airports and ANSPs on measures to reduce the environmental impact of aviation. With technologies available today, significant opportunities remain to reduce actual aircraft fuel burn and should be prioritised. Notably, airspace optimization and initiatives to enable more direct aircraft routing can achieve substantial emissions reductions that would, in some regions, surpass the contribution of SAF or fleet renewal in the near term. IATA encourages all stakeholders to maintain open and transparent dialogue and engage collectively to seek viable solutions to achieving sustained emissions reductions.