Climate assessment of innovative mitigation strategies towards operational improvements in aviation

D1.4 – Report on the selection and review of operational improvements to be investigated

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CLIMOP Consortium

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

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Executive summary

In its first year of activities, the ClimOp project has made an inventory of the currently known operational improvements (OIs) that hold the potential to reduce the impact of aviation on climate and of the available key performance indicators to quantify the effect of these OIs on climate and on the aviation stakeholders, including airports, airlines, air navigation service providers, manufacturers, and passengers. In particular, the ClimOp deliverable "D1.3 – Report on the assessment of operational improvements against identified KPIs" presented a preliminary assessment of 25 OIs classified in four categories: climate-optimised operations of the airline network, climate-optimised trajectories, operational and infrastructural measures on the ground, and operational measures at regulatory level. The subsequent step was to select the subset of these OIs which will be studied in detail in the continuation of the project and particularly in the Work Packages 2 and 3. The present deliverable reports on this elicitation process performed by the ClimOp consortium.

Section 2 of this document describes the adopted selection criteria, which include: the scientific relevance of the OIs within the specialised literature, the modelling feasibility of the OIs, the technological readiness of the OIs, the requirements that the final set of OIs covers the four above-mentioned categories of operations and distribute the burdens of implementing the measures across all aviation actors, a low cost/benefit ratio of the implementation, and the positive feedback from the stakeholder experts of the ClimOp Advisory Board.

This elicitation process led to the selection of 11 OIs. Each of these will be investigated individually or in combinations with others in the two and a half years until the end of the ClimOp project. Section 3 presents a preliminary description of the methods which will be adopted to calculate their impact on climate and on the relevant stakeholders. These methods include, for example, a variety of modelling tools and numerical simulations that calculate the variations in multiple parameters which follow from the implementation of each OI. Examples of these parameters are the total fuel consumption, the duration of the flights and other operations, the emissions of greenhouse gases and pollutants. The environmental and operational consequences of the variations of these and other parameters will be estimated in terms of the climate response they generate, which will be computed with climate models, and of the increase (or decrease) of burden for the stakeholders (for example additional costs or savings, complexity of operations, etc.). A preliminary list of the models and databases that will likely be adopted for the assessment of the OIs is presented in Appendix A.

1. Introduction

1.1 ClimOp project

The aviation industry contributes to human-made emissions mostly by releasing carbon dioxide (CO_2), water vapour (H_2O), nitrogen oxides (NO_x), sulphur oxides (SO_x), soot and sulphate aerosols. In terms of *anthropogenic radiative forcing*[1], 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 cutting its emissions and implementing 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 hereinafter) 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 will be assessed, taking CO_2 and non-CO_2 effects into account. In addition, in collaboration with the stakeholders in the consortium and the Advisory Board, ClimOp will evaluate the impact of these OIs on airports, airlines, air navigation service providers (ANSP), manufacturers, and passengers. As a result, ClimOp will develop a body of harmonised, most-promising mitigation strategies based on the alternative sets of OIs and will provide recommendations for target stakeholders on policy actions and supporting measures to implement the alternative sets of OIs.

1.2 Work package 1

The scope of Work package 1 (WP1) is to determine the OIs that have a large potential to mitigate the impact of aviation on climate. The first steps in this direction consisted of compiling an exhaustive inventory of all possible OIs that can be introduced, from the choice of ground equipment to changes in the allowed routes and specifically designed regulations to encourage

[1] The anthropogenic radiative forcing is the influence human activities have in altering the balance of incoming and outgoing energy in the Earth-atmosphere system.

climate-friendly practices [5], and identifying all possible KPIs that enable a quantitative assessment of these OIs [4]. These KPIs include climate impact metrics and metrics representing stakeholders' needs and priorities. The purpose of this approach is to ensure that requirements such as operation safety, practical feasibility, and long-term economic sustainability are taken into account in the analysis. The activities of WP1 continued with an analysis that associated each OI with the most relevant KPIs that capture its consequences for the climate and the involved stakeholders [6].

The subject of the present report is a preliminary selection of the most-promising OIs, for which a quantitative study will determine the climate impact mitigation potential (in the context of WP2). If the quantitative assessment performed in WP2 confirms their potential, the analysis will continue with the elaboration of strategies leading towards their implementation by different stakeholders (as part of the activities of WP3). This process will be carried out iteratively to balance the impact on stakeholders with the overall goal to reduce the effects of aviation on climate. The outcome of this iterative process will be a set, or a list of alternative sets, of feasible OIs with the highest potential to minimise aviation's contribution to climate change.

1.3 Deliverable D1.4 in the Project's context

The Deliverable D1.4 "Report on the selection and review of operational improvements to be investigated" provides a first selection of OIs listed in D1.3 as a basis for future assessment carried out in WP2 and WP3.
The OIs have been shortlisted according to a multi-step procedure described in detail in Section 2. In the first part, OI were scored by every partner on the basis of selection criteria. The vote scale ranges from 0 (no judgement) to 5 (very large, much agree). Selection criteria can be divided with a good approximation in two main groups; "consortium related" and "stakeholder related" criteria. Consortium related criteria include scientific interest, expected impact on climate and modelling capability while some stakeholder related criteria are stakeholder implementing capability, cost/benefit ratio and actual availability. All the rankings from the partners are then integrated to obtain a general preliminary ranking. All the partners then weighted the OI through a pairwise comparison of questions. DLR analyzed the ranking results through an AHP (Analytical Hierarchy Process) analysis, an established method for decision making, in order to decide how to mix the partner's votes. Five different approaches were simulated, and the resulting rankings were calculated using average, median, excluding outliers and considering single partners ranking. The AHP results were discussed and the final OI ranking have been selected, considering this statistical approach but also taking into account qualitative criteria in order to cover all the project area of investigation.

The selection brought the initial number of OIs from 25 to 11. This report covers four different categories of OIs: Climate-optimised operation of the airline network (five OIs), Climate-optimised trajectories (two OIs), Operational and infrastructural measures on the ground (three OIs), Operational measures at regulatory level (one OI).

The description of each OI is divided in two parts: in the first part, the impact on climate and on the involved stakeholders of each OI and also its advantages/disadvantages are presented; in the second part, it is introduced at an high-level the proposed methodology to study the OI's impact on climate and the KPIs/methods to evaluate its impact on stakeholders also in terms of feasibility/implementability.

As declared in the Description of the Action, the purpose of this report is to clearly identify the first round of OIs that will be more deeply examined in the D2.3 “Report on the climate impact of the first set of operational improvement options”. This deliverable belongs to Task T2.3: “Iterative climate impact assessment”.
In this task the combined simulation of air traffic and climate impact prepared in T2.1 and T2.2 is applied to the first set of OIs selected in this deliverable. The results of the assessment carried out in this task are used to refine the list of OIs in WP1 and create a second set of options, which will be finally assessed in the same way.

1.4 List of acronyms adopted in the present deliverable

Acronym	Meaning
AB	Advisory Board
AGTP	Absolute Global Temperature Change Potential
AHP	Analytic Hierarchy Process
ANSP	Air Navigation Service Provider
ATM	Air Traffic Management
ATR	Average Temperature Response
ATS	air traffic service
AU	Airspace User
CCO	Continuous climb operations
CDO	Continuous descent operations
CI	Cost Index
DOC	Direct operating costs
FRA	Free route airspace
ISO	Intermediate stop-over
KPI	Key Performance Indicator
LAQ	Local Air Quality
MAS	Multi-agent system
MIP	Mixed-integer programming
OI	Operational Improvement
SCO	Stepped climb operations
SDO	Stepped descent operations
SNP	Strategic network planning
WP	Work Package

2. Methodology for selecting the Operational Improvements

2.1 Selection criteria

The criteria to select the OIs, which will be subject to a further investigation during the ClimOp project, were established in a series of virtual meetings attended by all partners. During these discussions, it was agreed that the prerequisite for considering an OI for further analysis is that it holds a potentially positive impact on climate. In addition, criteria have been proposed and discussed among two main axes: *(i)* the OIs must be within reach of the consortium in terms of scientific knowledge and of modelling feasibility, and *(ii)* the OIs must be relevant and meaningful to the stakeholders, in that they recognise a benefit, for the climate but also their businesses, in implementing the proposed OIs. With these aspects in mind, the consortium decided to take into account:

- The scientific relevance of the OIs. That is, whether each OI is discussed and considered promising in the specialised literature in the sectors of climate change and aviation.
- The modelling feasibility of the OIs, which involves the capability of the partners to conceptualise how each OI would modify the current operations and state of the art, include these changes in the theoretical models of the relevant operations, and quantify the impact on the climate and the stakeholders. This criterion also includes the constraint that the modelling process must be completed within the duration of the project.
- The technological readiness of the OIs, which directly affects its timescale of implementation in everyday operations.
- The fact that the set of selected OIs covers all areas of operations, namely the airport operations, the regulatory level, the aircraft ground operations, and the operations at network and trajectory levels.
- The fact that the set of selected OIs guarantees a fair distribution of the burdens across all aviation actors. That is, the changes in the operation routine introduced by the OIs should not weight, in terms of costs and constraints, only on an individual stakeholder.
- A low cost/benefit ratio of the implementation, which means favouring OIs that are as seamless as possible to introduce and, concurrently that guarantee a large positive impact on climate and, when possible, an economic benefit to the stakeholders (e.g., optimised taxiing procedures are an advantage both for the climate and for the Airspace Users that consume less fuel).
- The feedback and informed opinions collected from the stakeholder experts of the ClimOp AB, who were surveyed about the potential and applicability of the complete list of OIs presented in D1.2 [7]. The results of this survey are summarised in Sect. 2.2.5.

To assess the 25 OIs reported in the deliverable D1.3 [6] against these criteria, the consortium progressed as explained in the following sections.

2.2 Selection process

2.2.1 Questions to guide the assessment

As a first step, the following twelve questions were produced to guide the assessment.

1. Does this OI have an expected positive impact on climate in terms of the reduction of CO_2?
2. Does this OI have an expected positive impact on climate in terms of the reduction of non-CO_2 species?

3. Has this OI been researched in the past, and is it considered scientifically relevant by the community and/or by the consortium?
4. Can the impact of this OI be quantified in the climate models?
5. Do you consider this OI to be relevant/impactful to the activities of Airlines and airspace users?
6. Do you consider this OI to be relevant/impactful to the activities of Airport operators?
7. Do you consider this OI to be relevant/impactful to the activities of ANSPs?
8. Would the Airports be capable of implementing this OI in their operations?
   (i.e.: the technology and the know-how are available and the limiting factors for the implementations are economic, regulatory, or else)
9. Would the Airlines be capable of implementing this OI in their operations?
   (i.e.: the technology and the know-how are available and the limiting factors for the implementations are economic, regulatory, or else)
10. Would the ANSPs be capable of implementing this OI in their operations?
    (i.e.: the technology and the know-how are available and the limiting factors for the implementations are economic, regulatory, or else)
11. Do you consider the cost/benefit ratio of implementing this OI to be satisfactory?
    (This question focuses on costs and benefits for the stakeholders)
12. Is this OI readily available/implementable?

2.2.2 OI assessment

At this point, each partner Organisation answered the questions, for each OI separately, with a value in a Likert scale from 1 to 5. Figure 1 shows an example of the OI assessment grid filled in by one of the partners.

To vote please use the following scale:
0= I do not feel I can give an expert judgment on this
1= Very small / Not at all/ I strongly disagree
2= Small / Not so much/ I disagree
3= Mild / Average / I neither agree nor disagree
4 = Large / Largely / I agree
5= Very large / Very much / I very much agree

Questions	OPERATIONAL IMPROVEMENTS																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	3	3	4	5	3	5	2	5	4	5	5	1	4	3	4	5	4	3	3	2	3	1	4	4	1
2	3	3	3	5	5	5	2	5	4	5	5	5	4	3	4	5	2	2	4	4	3	1	4	4	1
3	4	4	4	5	5	5	3	2	4	3	3	4	5	4	4	4	1	4	4	4	2	3	2	4	2
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	4	4	4	5	5	4	3	5	5	5	5	3	5	5	4	5	1	1	3	3	4	1	3	5	4
6	4	4	3	2	3	2	4	4	3	3	3	4	5	5	1	5	5	3	4	3	4	5	5	3	4
7	5	5	5	5	5	4	4	5	4	4	4	3	5	3	3	5	1	1	2	1	2	1	3	4	2
8	4	4	4	0	1	3	4	2	3	3	3	4	2	3	0	2	5	4	3	4	3	3	2	4	0
9	4	4	4	3	1	4	3	1	3	3	3	4	2	2	4	2	0	0	3	3	3	0	0	4	0
10	4	4	4	3	1	4	4	2	3	3	3	4	3	5	4	2	0	0	3	4	4	0	0	4	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	5	5	4	3	2	4	4	2	3	2	2	4	2	3	4	2	3	4	3	4	3	4	4	3	4

Figure 1. Example of the OI assessment filled by one of the partners. The OIs are numbered from 1 to 25 as in deliverable D1.3[6]**. The questions 1 – 12 are the same as in Sect. 2.2.1.**

Because the partners of the ClimOp consortium come from a variety of backgrounds, the option was given to vote 0 to indicate that the responding partner did not feel confident enough to give an expert judgment on a particular subject.

The assessment grids of all partners were subsequently collected, and an average was calculated for each pair of OI and question. In this process, the null values were excluded.

2.2.3 Ranking of the questions

The necessary step before calculating the ranking of the OIs was to assign a weight to each question to ensure that some desired aspects are prioritised with respect to others. For example, the reduction of CO_2 and/or non-CO_2 emissions should be given higher importance compared to the technological maturity of the OI. To achieve this goal, the consortium performed a pairwise comparison of all questions, as shown in Table 1. This exercise made it possible to arrange the questions according to the clear relative positioning of their importance.

The ranking obtained in this process reflects the relative importance of the selection criteria that lay behind each question and was subsequently converted into quantitative weighting factors to be used to calculate the scores of each OI, as explained in Sect. 2.2.4.

Table 1. Results of the pairwise evaluation of questions 1 – 12.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1												
2	2											
3	1	2										
4	4	4	4									
5	1	2	5	4								
6	1	2	6	4	=							
7	1	2	7	4	=	=						
8	1	2	8	4	8	8	8					
9	1	2	9	4	9	9	9	=				
10	1	2	10	4	10	10	10	=	=			
11	1	2	11	4	11	11	11	11	11	11		
12	1	2	12	4	12	12	12	12	12	12	11	

2.2.4 Ranking of the OIs

The final step to determine the quantitative ranking of the OIs was to adopt the analytic hierarchy process (AHP) [8] based on the scores assigned by each partner weighted with the relative importance of each question. For this purpose, it was necessary to initially convert the 1–5 values of the adopted Likert scale into 1–9 values to ensure consistency with the AHP scheme [9]. Different assumptions to treat this conversion led to similar weighting factors, only marginally affecting the ranking results. In this process, it is worth to mention that, in some of the questions, not all answers were consistent, reflecting the fact that different partners had conflicting opinions. To account for these differences, multiple approaches were tested: the arithmetical average of all scores, the median, the average weighted on the range or standard deviation of the values, and the average removing the outliers.

These different approaches gave relatively consistent results. In particular, while the exact ranking of each OI varies in the different cases, these variations are relatively limited, and consequently, the top ten and the bottom five OIs are robustly identified. As an example, the following Table 2 shows the final ranking of the 25 OIs adopting the median of the assigned scores, which is less sensitive than the mean to possible outliers.

Table 2. Ranking of the 25 OIs adopting the median of the scores assigned by the partners.

Rank	Operational Improvement
1	Flying low and slow
2	Continuous climb/descent operations
3	Free routing in high-complexity environment/flexible waypoints
4	Climate-optimised flight planning
5	Wind/weather-optimal dynamical flight planning
6	Single engine taxiing
7	Routing optimised for contrail (night) avoidance
8	Climate-optimised North-Atlantic Track System
9	E-taxi (tow truck or tug wheel) and hybrid taxi
10	Climate-optimised intermediate stop-over
11	Strategic planning: merge/separate flights; optimal hub-spokes/point-to-point operations
12	Limit “climate-unfriendly” aircraft operations
13	Trade flight frequency for aircraft size
14	Climate-restricted airspaces
15	Departure/arrival management extended to en-route airspace
16	Climate-charged airspaces
17	Performance-Based Navigations for landing
18	Optimal separation minima
19	Formation flying
20	Electrification of ground vehicles and operations
21	Environmental scoring
22	Renewable energy produced at airports
23	Voluntary initiatives to reduce CO2 emissions
24	Upgrade of the existing infrastructure according to energy efficiency criteria for the reduction of environmental impacts
25	Implementation of a monitoring system for the atmospheric emissions

2.2.5 Stakeholder consultation

The first AB workshop of the ClimOp project took place remotely on the 2nd of July 2020, on an interactive webpage hosted by the ClimOp official website. The main objectives of the AB

workshop were to collect feedback on the preliminary results produced in the early months of project activities, in particular on the OIs that were identified by the consortium to mitigate the impact of aviation, and KPIs to quantify the effect of these OIs on climate and on the aviation stakeholders. A report of the AB Workshop activities is available on the ClimOp website [10].
In this context, the stakeholders were asked a series of questions to determine the OI which, in their opinion, currently show the greatest potential to reduce the impact of the aviation industry on climate. The stakeholders identified the following in-flight procedures in the airline network and trajectory areas of operation: avoiding climate sensitive areas, optimal hub-and-spoke and point-to-point network, climate-optimised approach procedures (including CCO and CDO), and flying low and slow. The following improvements of ground operations and at regulatory level were also considered very promising: efficient taxiing (which includes single-engine, electric or hybrid tow-truck or tug-wheel taxing), the electrification of ground equipment for airport operations, and the environmental scoring of aviation operations with the aim of promoting those that are more climate friendly.

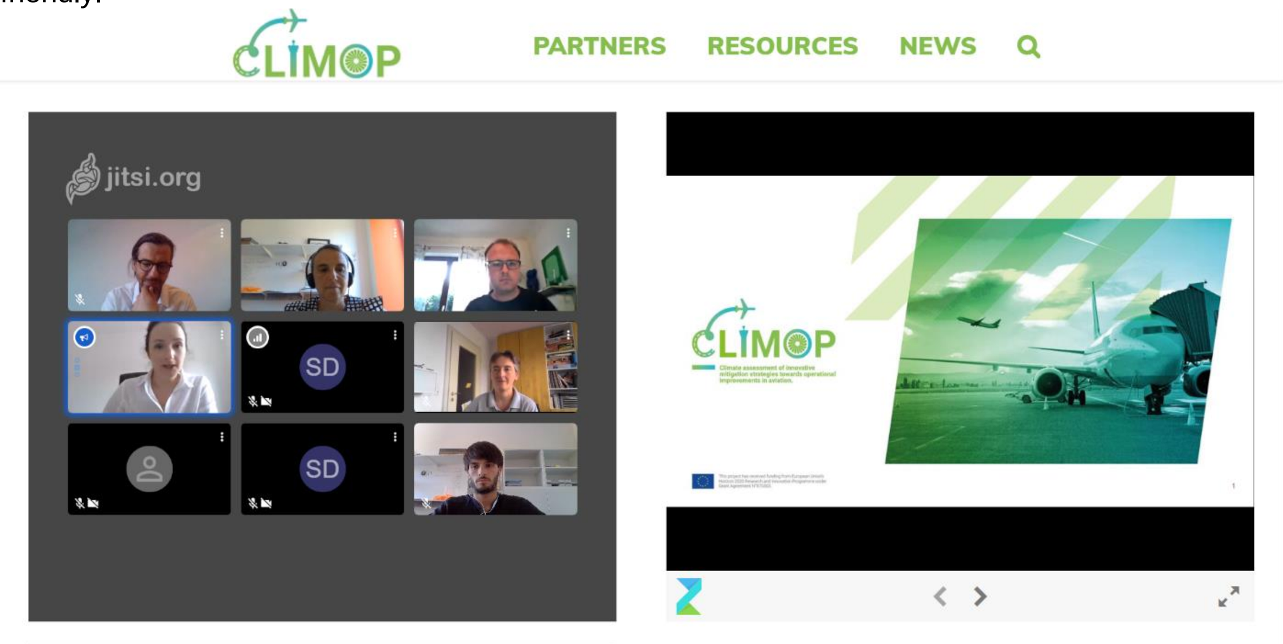

Figure 2. Screenshot of the virtual Advisory Board Workshop on the 2nd of July 2020. Left panel: the participants to one of the two focus-group discussions. Right panel: the first slide of the presentation of the preliminary results of ClimOp streamed through Mentimiter.

2.3 Results of the selection process

The results of the ranking process described in the previous sections were discussed by the ClimOp partners. The final list of OIs to be analysed during the project was defined by the OI ranking in combination with the following essential considerations:

a. All OI areas are covered, namely operations of the Airline network, climate-optimised trajectories, ground and operations, and actions at the regulatory level.
b. All timescales are covered, from improvements readily implementable, in potential, to those that are not yet mature enough and can be introduced in the medium or long term.
c. All aviation stakeholders have at least one OI relevant to them and will be engaged in future analysis.
d. The selection is aligned with the feedback of the ClimOp AB.

This final round of selection resulted in the following list of eleven OIs in Table 3. The first round of assessment will be performed as part of WP2 to determine the potential of these OIs to reduce the impact of aviation on climate. Subsequently, in the second half of the ClimOp project, this selection will be refined for the second round of assessment.

Table 3. Selected OIs and their preliminarily-assessed, potential timescales from implementation. A short/medium/long timescale indicates an OI potentially implementable in, approximately, less than three years/ less than ten years / more than ten years, respectively.

	Area of operation	Selected OI	Potential timescale for the implementation
1	Airline network	Flying low and slow	Short-intermediate (does not require new technology, on the long term aircraft might be optimised to fly low, congestion issues might arise that require improvement in the separation system)
2	Airline network	Continuous climb/ descent operations	Short
3	Airline network	Free routing in high-complexity environment / flexible waypoints	Intermediate-long
4	Airline network	Climate-optimised flight planning	Intermediate-Long (Climate response models have to be thoroughly verified before being put in use. Once the models are shown to work positively, a comprehensive agreement has to established with multiple sectors)
5	Airline network	Wind/weather-optimal dynamical flight planning	Intermediate
6	Trajectory	Strategic planning: merge/separate flights; optimal hub-spokes/point-to-point operations	Intermediate-long (does not need new technology but requires a comprehensive agreement for the planning of the trajectories with multiple actors)
7	Trajectory	Climate-optimised intermediate stop-over	Short-Intermediate (does not require new technology and thus could be realized immediately, on the long term aircraft design may be optimised for such type of operations)
8	Ground operations	Single engine taxiing / E-taxi (tow truck or tug wheel) and hybrid taxi	Short-intermediate (single engine taxiing does not require new technology but the technology for e-taxi and hybrid taxi is still not in a mature phase)
9	Regulatory	Promote “climate-friendly” flights	Intermediate

10	Airports	Electrification of ground vehicles and operations	Short-intermediate (technology is available, requires significant investment)
11	Airports	Upgrade of the existing infrastructure […] for the reduction of environmental impacts	Short-intermediate (technology is available, requires significant investment)

3. Results of the first OI selection

The following sections of this report cover OIs in four different categories, namely: five OIs related to climate-optimised operations of the airline network, two OIs to introduce climate-optimised trajectories, three different operational and infrastructural measures on the ground (specifically, one related to ground operations and two to airport operations and infrastructure), and one type of operational measures at the regulatory level.

3.1 Flying low and slow

3.1.1 Description of the OI

This Operational Improvement aims at systematically reducing the cruise altitude of flights relative to today's typical flight altitudes, e.g., from 36.000 ft to 28.000 ft and adjusting the cruise speed accordingly to remain within the flight envelope of the aircraft. Only minor preparations are required to implement this operational measure if existing aircraft are used. Additional potential can be gained if aircraft are designed for lower altitudes and lower cruise speeds, which is beyond the scope of the ClimOp project.

Studies have shown that the non-CO_2 effects of the flight can be significantly reduced, as the aircraft would avoid releasing NO_x emissions in altitudes, in which their net radiative forcing is at maximum (tropopause), and the contrail coverage at mid-latitudes can be reduced [11], [12] (and references herein). The associated climate impact metrics, such as Average Temperature Response (ATR), might therefore be improved. Further studies would be needed to identify the routes and scenarios for which the non-CO_2 benefits prevail over the penalties due to the increased CO_2 emissions.

Aircraft flying significantly below their optimum altitude burn additional fuel. Moreover, the reduced cruise speed leads to an extension of flight time. Both parameters mainly drive the operating costs of the flight, so for the **aircraft operator** (airline), the main KPI, direct operating costs (DOC), will be degraded. As long as slack times at the destination airports are high enough, e.g., in case of some long-haul flights, the flight time extension might not be problematic from a fleet operations perspective. However, in the majority of practically occurring situations, an adjustment of the schedule and potential connections would be necessary. Also, the increased CO_2 emissions associated with the additional fuel burn may cause additional fees for the airline (emission trading or offsetting).

For **passengers**, as direct customers of the airlines, this might, in turn, lead to higher ticket prices and CO_2 compensation fees. Furthermore, the increased flight time would not be preferable from a passenger's perspective, in particular in the case of connecting flights.

For **Air Traffic Management**, particularly the Air Navigation Service Providers, the concept could lead to higher demand on certain lower cruise flight levels. This might create safety issues and pose a higher workload to the air traffic controllers, if widely used, and might lead to airspace congestion which would risk cancelling out the climate benefits because of additional fuel burn.

No specific impact is expected on the **airport** level.

3.1.2 Description of the assessment process

For the impact assessment of the OI a modeling chain needs to be in place that is capable of evaluating the concept on a fleet/global level whilst capturing the important effects of changing the cruise altitude and speed on mission level. For the latter, a trajectory simulator should be used (e.g., DLR's TCM), which applies advanced aircraft performance models, that are accurate enough

to capture the sensitivities of fuel consumption to changes in altitude and speed. This trajectory simulator can directly compute the impact on fuel burn and flight time, which can be used to calculate KPIs relative fuel changes (K3) and relative time changes (K25.1) with respect to the reference flight, which is e.g., conducted in the cost-optimal or fuel optimal manner. It should be complemented by a DOC model, that calculates the airline's direct/cash operating cost changes (K38) for the flight based on block fuel and time. In order to calculate climate metrics, an established tool chain containing an emission calculation and gridding tool, GRIDLAB, and the climate response model AirClim can be used [13]. These tools determine for each point along the aircraft trajectory the gaseous emissions released from the engine and calculate their respective impact on climate in terms of Radiative Forcing (K48), surface temperature (K49) or Average Temperature Response over 100 years ATR100 (K1.2).
In addition to this mission level assessment, an outer simulation loop is required, that performs the mission analysis for every flight within a reasonable air traffic scenario. This set of flights needs to be carefully defined prior to the analysis based on the desired scope of the study (e.g., limited to selected aircraft types only, or specific to a geographic region/traffic flow). By varying the cruise altitude and Mach number in each mission in an exhaustive manner covering defined pairs for altitude and speed, a Pareto frontier, that trades climate impact reductions with cost increases, can be calculated, which provides the basis for the selection of optimal (acceptable from a cost point of view) operating conditions. Finally, using an Air Traffic Flow Management model, the resulting traffic scene can be analysed with respect to congestion (K23) and controller workload (K58) in particular airspaces or flight levels per period of time [14]. Thus, also the impact on ATC will be evaluated. To determine the effect on passenger acceptance (K59.1), the block time and ticket price estimations based on COC changes can be used. An appropriate model needs to be developed in the course of WP2.

3.2 Continuous climb/descent operations

3.2.1 Description of the OI

Continuous climb and descent operations (CCO/CDOs) are flown at airports in varying numbers. This concept lets aircraft follow a continuous climb or descent path, where currently many followed paths are still stepped. The vertical path of these paths is sketched in **Figure *3***.

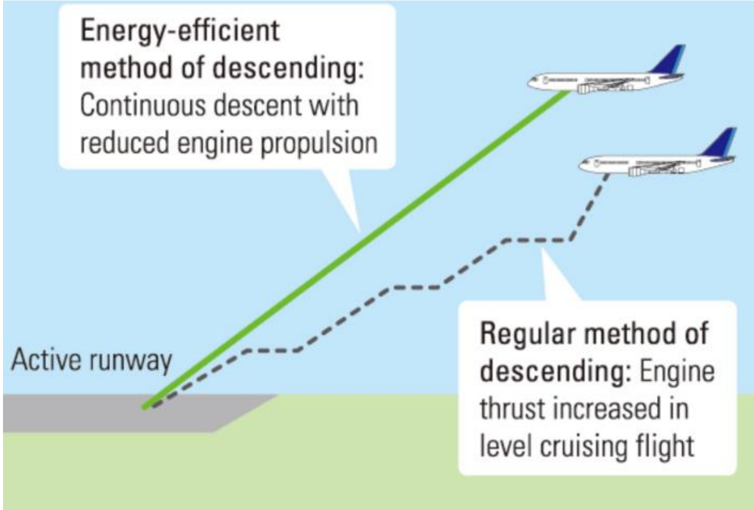

Figure 3: Sketch of a CDO approach (green line) versus a stepped approach (dotted line). The original illustration is shown as Figure 1 of [15]

Due to operational barriers, which can be overcome, CCO/CDOs is not always possible [i]. Compared to SCO/SDOs, CDO/CCOs have an impact on several factors. First of all, the flight path will differ, meaning that in many cases aircraft fly higher for a longer time and while descending will mostly fly above current vertical profiles, helping to reduce noise levels [15] under the flightpaths. Next to this, aircraft can often fly in a clean configuration for a longer time, reducing fuel consumption and noise emissions. Since the vertical flight path changes, the distribution of emission quantities at certain altitudes also changes, leading to different climate impacts for several emissions.

There are several operational barriers as mentioned earlier (Sect 2.2 of [6]). One of these barriers is the lack of possibilities to correct the trajectory of the aircraft due to increased separation minima, which is important for the safe handling of the aircraft by air traffic control. Additionally, the climb performance of different aircraft can also widely vary, which is a complex factor for climb operations. These barriers can be lowered by different strategies; for instance, by further optimization of the balance between peaks and low traffic density hours, or implementation of e.g., fixed routes and/or interval management.

As described, some of the barriers are due to air traffic capacity and/or controllability to safely manage the traffic. However, airlines potentially gain from the implementation of full CCO/CDO. **Figure *4*** shows an optimum Cost Index (CI) with respect to time-dependent costs, fuel cost and CO_2 emissions. It is expected that, with respect to current operations, airlines will not only save fuel, but also time and both related costs. Dependent on the strategy and technological resources of air traffic control, the impact on the airport may vary from less throughput to similar throughputs.

The deployment of CCO and CDO throughout will be beneficial to all ATM system stakeholders. For a deployment in Europe, the deployment has the potential to save over 1Mt CO_2, 1-5dB noise, and up to €150 million will be saved in costs [15].

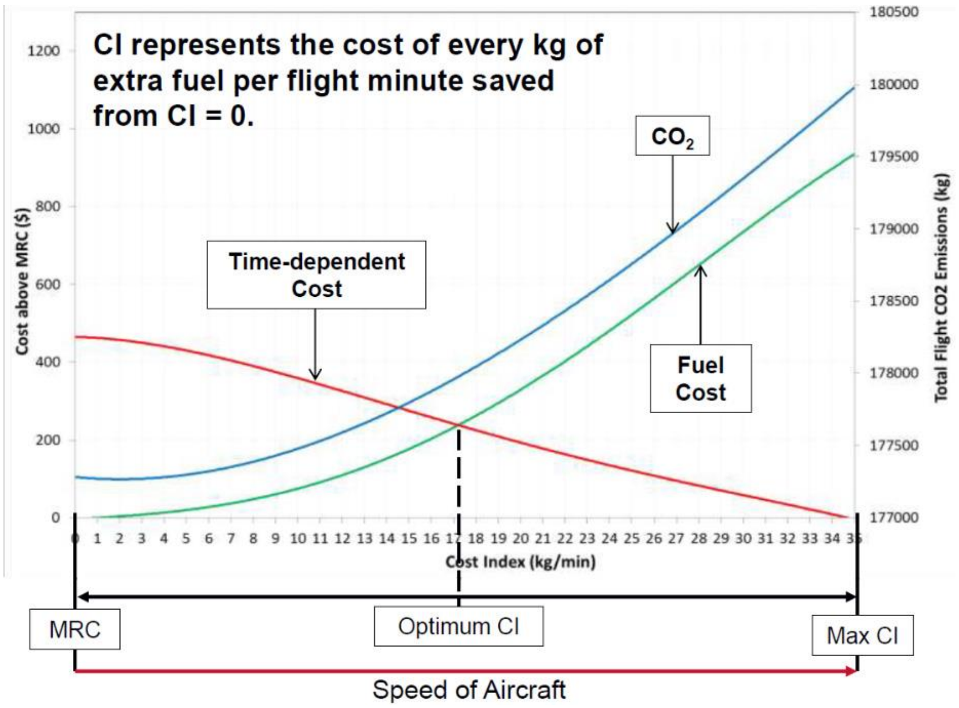

Figure 4: Optimum Cost Index for CCO/CDO operations with respect to time-dependent cost, fuel cost and CO2 emissions (cf. Fig. 5 of [15]**)**

For an effective and harmonised implementation in Europe, a CCO/CDO Task Force was created in 2015 [16]. Currently, this task force has developed a CCO/CDO Tool Kit to support CCO/CDO implementation in Europe, which consists of the European CCO/CDO Action Plan, CCO/CDO performance dashboard, and available resources [15].

3.2.2 Description of the assessment process

As discussed, this OI has an impact on several stakeholders and KPI's. In order to assess the impact of this OI, the field of impact will be split into climate and stakeholder impacts.

Impact on climate
Determining the climate impact of CCO/CDO, with respect to current operations, will be done by obtaining several types of emissions. These emissions should be calculated in a manner that they are comparable to the results of other OI's. This means that the initial conditions and boundary conditions of simulations should be the same. The impact on climate due to implementation of CCO/CDO will be dependent on CO_2, NO_x, PM, H_2O and other emissions. For some species, also the location at which the emissions take place is of importance for climate impact.

Different scenarios will be simulated, where one (or several) are representative for current-day operations and others for future operations with more CCO/CDO operations. By evaluation of the location and amount of emissions, the climate impact of the different scenarios can be compared. For this a tool needs to be used that can simulate aircraft movements and specified flight procedures and calculates the emissions from this input. Furthermore, this or a separate tool should be able to translate emissions at certain points in space to a climate impact. Tools, models and data sources that can be used for this are:

- BADA [17]
- Traffic Manager [18]
- NARSIM [19]
- Leas-iT [20]
- Doc29 noise model [21]

Impact on stakeholders
The impact on stakeholders is very diverse. CCO/CDO has an impact on many different areas both on a global climate scale and on a local environmental scale, which can be monitored by several KPI's, namely;

- Operating costs (**airlines/airports/ATC**)
    - Fuel costs – deduce from K3 (fuel flow)
    - Labour costs
    - Maintenance cost – deduce from K5 (maintenance frequency)
    - Investment costs for equipment
    - Training costs for pilots and air traffic controllers
- Flight time (**airline**) – K17
    - Per flight
    - Cycles per day
- Safety (**ATC**)
- Throughput (**airport**/**ATC**) – K26.3
- Revenues (airline/airport/**ATC**) – K39
- Noise (**residents near airports**) – K47
- Local Air Quality - LAQ (**residents near airports**)
- Acceptance among local communities near airports – K59.2

In order to determine the values for these KPI's, a combination of numerical models and interviews with stakeholders will be used. With numerical models, parameters such as fuel use, flight time and throughput can be calculated. Maintenance costs will be calculated from the engine power setting profile and labour costs are related to flight times. To determine the safety-related KPIs, a Safety Assessment will be carried out.

Feasibility and implementability
Feasibility and implementability are dependent on several factors, such as - the traffic density at and around the airport, the ability to train pilots and air traffic controllers and the overall benefits in terms of emissions and noise reduction, flight time and costs. In order to assess these factors, the impact on stakeholders, as discussed, will be evaluated through modelling by the ClimOP team and compared with answers from stakeholder interviews. From stakeholder interviews, insights on stakeholder decision making and the factors influencing it, as well as on challenges and solutions from real-life implementation, will be gained as part of the feasibility and implementability assessment.

3.3 Free routing in high-complexity environment/flexible waypoints

3.3.1 Description of the OI

Free Routing is the ability of an Airspace User (AU) to plan a route between defined entry and exit points. In a free-route airspace (FRA), route planning is possible according to user-related needs without reference to a fixed air traffic service (ATS) route network. In this case, AUs can fly their optimal tracks irrespective of existing ATS routes. In this study, the only constraint in the FRA will be the predefined entry and exit points, and the AUs will not be subject to the defined ATS routes. The concept results in better cost-efficiency and reduces the impact on the environment by decreasing fuel burn and greenhouse gas emissions. The beneficial effect of the free routing concept on climate could also be enhanced by considering the climate-related phenomena during the flight planning process of AUs in the FRA.

The stakeholders that have to invest and derive mainly benefit from the FRA concept are AUs and ANSPs (Air Navigation Service Providers). FRA brings significant benefits to the AUs as they are able to fly more efficient profiles in terms of costs and CO_2 impacts, using less fuel, hence reducing aviation's environmental footprint. However, when non-CO_2 effects are not considered during trajectory planning, the improved profiles could not lead to the optimum impact on climate. ANSP tasks could become more complicated since the trajectories are more variable and flexible. In high complexity and/or cross-border environment, the potentially high variability of the traffic demand could also lead to an increase of ATCOs workload. However, any negative effects could be expected to be counterbalanced by the reduction in the number of conflicts in a given sector by spreading the possible conflict points all over the sector areas [22]. It is also observed that, in a cross-border operation, FRA can deliver a decrease in controller workload, with a reduction in evaluation and coordination tasks, fewer radio transmissions, and enhanced traffic predictability [23]. The overall effect is not clear, and controller workload also depends on decision-support tools. Because of the paradigm shift in the operation environment, advanced decision-support systems for controllers in visualization, conflict detection, resolution options assessment, screen-to-screen electronic coordination support will be required. These systems will stabilize or decrease the controller's workload, and lead to additional investment costs for air traffic control services.

The main advantage of the free routing concept is the ability of the AUs to optimise their flights in line with individual operator business/military needs without reference to the fixed ATS routes. FRA will be beneficial for AUs in terms of fuel efficiency, flight emission reduction, and flight predictability without degrading safety and capacity. Besides, the free routing concept could reduce the number of conflicts in a given sector by spreading the possible conflict points all over the sector areas, and airspace capacity could be improved. FRA can also help to create a greener airspace by having a positive impact on greenhouse gas emissions via trajectory optimisation. Moreover, FRA could lead to shorter travelling times. However, the concept will result in additional investment costs for advanced decision support tools, and also an additional investment in the training of ANSPs for both basic and advanced solutions. Besides, it could be difficult to implement the free routing concept in congested and saturated airspace.

3.3.2 Description of the assessment process

Mathematical models will be used to assess the free routing concept. In the modeling environment, there will be an aircraft performance model [24] for the simulation of aircraft motion. The aircraft performance model will be a set of nonlinear differential equations that is utilized to drive the aircraft dynamics in which it incorporates only forces acting on the aircraft. The aircraft model will be based on BADA (Base of Aircraft Data) [17], and also consists of information about the fuel flow and released emissions. In addition to the aircraft model, there will be a trajectory tracking algorithm [25] to generate the required control inputs to follow a reference trajectory. This algorithm is used to follow the planned trajectory. We are planning to implement the free routing concept through the use of Direct Routing for flights both in cruise and vertically evolving within a high complexity environment. In this case, the aircraft will fly the direct routes between entry and exit points that are obtained from real flight plans. A conflict detection and resolution algorithm [25] could also be used for the separation assurance. As an alternative scenario, the trajectories could be optimized using optimal control techniques [26]. In this case, flight trajectories are generated by solving optimization problems constructed using dynamic and algebraic path constraints such as aircraft's equations of motion, performance parameters, emission inventories, restricted areas, conflict constraints, etc. This method is considered as a backup strategy for the assessment of the free routing concept.

The released emissions will be used to understand the impact of the free routing concept on climate. As already pointed out, mathematical models will calculate the number of emissions released by aircraft operated in a FRA, and also in a standard airspace. The comparison of a reference scenario for current operation and a scenario of operation in a FRA will quantify the impact of the concept relative to the current operation. The considered set of emissions will contain CO_2 (K2.1), NO_x (K2.2), H_2O (K2.3). The impact of the released CO_2 emission on the global temperature response will also be evaluated using pulse AGTP (Absolute Global Temperature Change Potential) for CO_2 [27]. Another KPI (key performance indicator) used to assess the free routing concept will be fuel flow (K3). Fuel flow (K3), on-time performance (K21.1), and routing efficiency (K25.1) will be used to assess the impact of the concept on AUs. Travel time (K33) could be also evaluated to analyse the effect of this OI on passenger pleasure. To evaluate the effect of this OI on air traffic control, controller workload (K58) will be utilized. Controller workload will be estimated using the average number of sector entries, vertical movements, and potential interactions [28], [29]. These listed KPIs can be calculated using the results of the numerical simulations based on the proposed mathematical models. The feasibility and implementability of this concept could also be evaluated analyzing the calculated KPIs.

3.4 Climate-optimised flight planning

3.4.1 Description of the OI

Climate-optimised flight planning aims at avoiding regions, in which aircraft emissions considering atmospheric processes, including transport, physics and chemistry, lead to a relatively high impact on climate, by means of an adequate flight planning prior to departure. This takes into account, the overall impact of aviation on the climate. This includes both CO_2 and non-CO_2 effects (from NO_x, water vapour and contrails). Since this OI directly focuses on mitigating climate impact, it is expected to have a large potential for a positive influence on climate.

Current estimates [30] show 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). The reader is referred to Table 2 in [31] for additional details that compare 0% to 25% climate reduction for Trans-Atlantic flights under a specific weather pattern. When other stakeholders are taken into account, the cost could increase further but this does not discount the possibility of achieving an even larger climate impact reduction. Some flights require larger deviations from the fuel and cost optimum trajectory and thus create higher operating cost penalties. 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.

The main advantage that favours its implementation is that through the use of real-time capable climate response models, the anticipated climate impact of the emissions can be determined instantaneously by having relevant and reliable information from weather forecasts. By using this information in a flight trajectory module, regions, where high climate impact is expected, are avoided. In addition to the cost increase, a possible disadvantage includes the impact on ATM as congestion may increase on some flight level, so there will be an increased ATC workload for monitoring the flight corridor and planning the flight schedule.

3.4.2 Description of the assessment process

To carry out the assessment of the OI, the work will be entirely computational in nature. A software called Modular Earth Submodel System (MESSy) [ii] will be used. MESSy provides an interface to couple various submodels to a base model with flexible complexity. Currently, two ClimOP partners are directly part of the MESSy consortium and make regular contributions are DLR and TU Delft.

An earth-system model called EMAC [32] will be used, which contains various sub-models. The main submodels that are relevant to this OI assessment are ATTILA, AirTRAC, AirTraf , ACCF [33] and RAD [34]. ATTILA is a tool which allows to perform a Lagrangian Trajectory Analysis within the global earth-system model. With the submodel AirTRAC reactive species can be transported on such Lagrangian trajectories, and chemical and physical processing studied. AirTraf is a tool to calculate aircraft trajectories for a given set of city pairs and optimise flight traffic based according to various objectives. The unique aspect of AirTraf is that it uses online-calculated weather conditions as inputs to the aircraft trajectory optimization routine, which allows the consideration of different weather patterns while planning trajectories. The other sub-model called ACCF uses prototypic algorithmic climate change functions and computes climate change functions in the model domain, which quantify the anticipated climate impact of an aviation emission based on the local weather conditions. If required, a Trajectory Optimization Module (TOM) available in DLR, which is based on an optimal control approach to perform unconstrained multi-criteria trajectory optimization and which has already been successfully applied in previous research for climate-optimized flight planning [35], can be applied. In addition to these models, we are assessing to use an Airport-Centric Queuing Network Model [36] for simulation of delay propagation across the network considering airports' capacity limits and disruptive events. Using this model, the departure times that are affected by the delay propagation can be rescheduled.

This climate impact can be directly estimated in terms of, e.g. ATR20 (K1.1), which is one of the chosen climate metrics for this OI as documented in D1.1 [37]. However, in order to estimate ATR100 (K1.2) the sub-model has to be further expanded. Lastly, the sub-model, called RAD, simulates radiative transfer, which helps in computing the Radiative Forcing (K48). Additionally, comparisons can be made with respect to cost-optimised air traffic that focuses more on lowering the flight operating cost by minimizing fuel consumption and hence, CO_2 emissions. Figure 1 [38] shows a sample simulation setup that focuses on analysing the impact of aviation NO_x emissions from climate optimised (with respect to ozone aCCFs) and cost optimised air traffic.

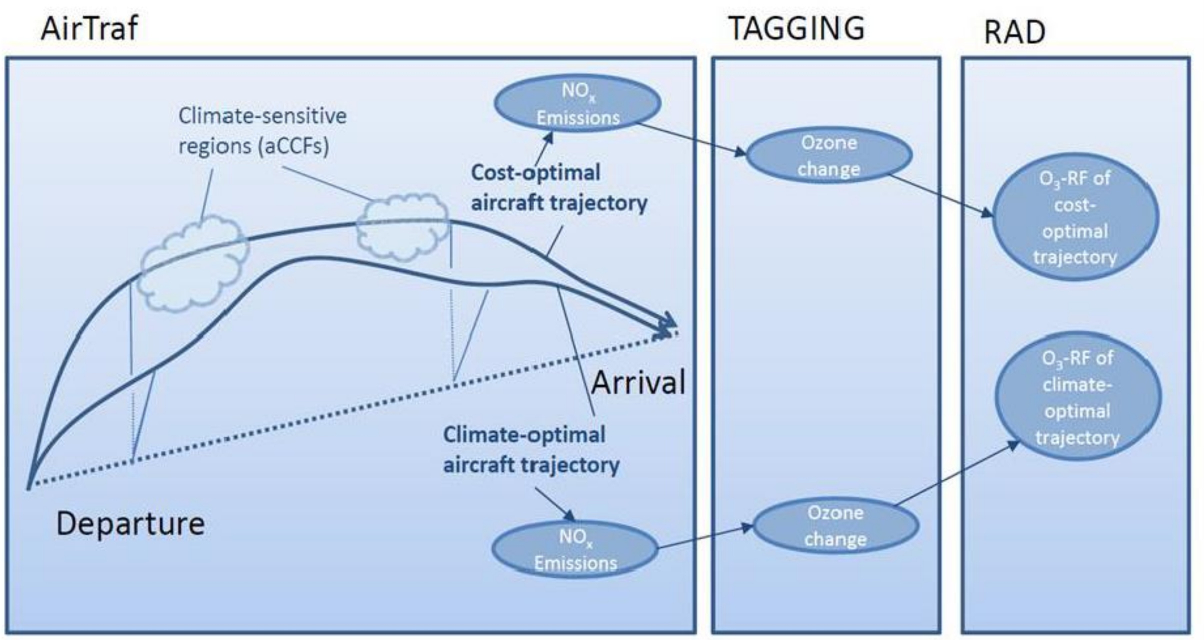

Figure 5. Simulation setup for climate-optimised routing with respect to aviation NOx emissions [36].

The main stakeholders involved in this OI are Airlines, ATM and air trajectory planners. Currently, it is possible to measure fuel flow (K3) and airline expenses (K38) which are relevant to assessing the impact on airlines. Airline expenses are driven by e.g. fuel burn, flight time and aircraft utilization. However, it is not currently known how implications on ATM and air trajectory planners can be established. Here the KPIs that could be used are in relation to safety by evaluating possible conflicts of various flight paths and analyzing the possible congestion of the flight corridor. Using the average number of sector entries, vertical movements, and potential interactions [28], [29], controller workload (K58) could be quantified to analyze the impact of this OI on air traffic controllers. To assess the effect on passengers, travel time (K33) could be used.

The initial results for climate-optimised routing are positive while taking into account various climate KPI and few cost-related KPIs. However, computing KPIs related to ATM and air trajectory planners are also essential. Once this is clear, the implementability can be evaluated more easily.

The geographical region that will be analyzed has not been decided yet. The impact of the concept in climate has been studied for different airspaces. The project REACT4C evaluated the impact of

climate-optimised routing strategies on the North Atlantic airspace [35], whereas the project ATM4E [35] focused on the European airspace, providing detailed analysis for a one-day case study over Europe [39].
To the best of our knowledge, the combined European, North Atlantic, and US region has not been evaluated from the perspective of climate-optimised planning, and the concept has also not been implemented on a global scale. From an implementation perspective, focusing on the combined EU-US region or global traffic network could contribute to the scientific community. As a first step, a detailed literature study will be conducted to figure out whether focusing on one of these regions is a contribution or not. However, there could be also some difficulties with the analysis of climate-optimized flight-planning in these regions such as data unavailability and long processing times of model components. Besides, another contribution could be the assessment of the impact of climate-optimized planning on different stakeholders. Hence, focusing on a previously analyzed region, the strategy could be evaluated from the perspective of different stakeholders. After a comprehensive analysis, we will decide on the geographical region.

3.5 Wind/weather-optimal dynamical flight planning

3.5.1 Description of the OI

Wind/weather-optimal dynamical flight planning concept corresponds to optimizing flight trajectory by considering the available wind and weather information to minimize the negative impact of wind/weather on the operation. In our study, in addition to wind information, the concept will also evaluate the relative humidity and environmental temperatures during the optimization process to avoid potential contrail formation areas [40]. While considering wind during optimization decreases fuel burn and greenhouse gas emissions, avoiding potential contrail formation areas could mitigate the green-house effect of contrails. Hence, it is expected that the concept will have a positive impact on the climate, as was shown in earlier studies, e.g. [39], [40]

The main stakeholders that will be affected by this concept are AUs and ANSPs. AUs will implement more efficient operations because of optimized costs considering wind and weather phenomena. From the standpoint of air traffic control, the concept may lead to an increase in the workload of ANSPs because of the high demand for specific wind/weather-optimal routes and altitudes. The concept could lead to more efficient approach operations by decreasing the deviation from the planned trajectories, so runway throughput could also be enhanced, which is a positive effect on airports.

The main benefits of the concept could be the reduced fuel consumption and emissions, mitigated the green-house effect of contrails, and improved runway throughput, which may favour its implementation. However, the concept also could lead to excessive demand for some routes and altitudes.

3.5.2 Description of the assessment process

For the assessment of this OI, the ClimOp partners will benefit from optimization-based control techniques [26] in which the planning problem is transformed into an optimization problem to generate optimal control strategies with regards to defined objectives. In this approach, dynamic constraints that come from an aircraft performance model, performance limits, and other restrictions are presented as the constraints of the optimization problem. In this study, the aircraft performance model will be based on BADA [17], and also consist of information about the fuel flow and released emissions. The wind and weather information will be obtained from the dataset collected by The National Center for Atmospheric Research [41].

The impact of the wind/weather-optimal planning on climate will be evaluated using released emissions and Absolute Global Temperature Change Potential (AGTP) [27]. The released emissions will be calculated based on the fuel consumptions as a result of following the optimal trajectories obtained by solving the constructed optimization problems. The considered set of emissions will contain CO_2 (K2.1), NO_x (K2.2), H_2O (K2.3). The impact of the flown trajectories on the global temperature response will be evaluated using pulse AGTP for CO_2 and pulse AGTP for contrails. For evaluation of the concept from AUs' perspective, fuel flow (K3), on-time performance (K21.1), and routing efficiency (K25.1) will be used. Controller workload (K58) can be presented as an indicator of the effect of this OI on air traffic controllers. Controller workload will be estimated using the average number of sector entries, vertical movements, and potential interactions [28], [29]. Safety level could also be evaluated benefiting from the controller workload, the frequency and spatial distribution of the encounters and conflicts, and the time in advance the conflict. These listed KPIs can be calculated using the solutions of the aforementioned optimization problems. The feasibility and implementability of this concept could also be evaluated analyzing the calculated KPIs.

3.6 Strategic planning: merge/separate flights; optimal hub-spokes/point-to-point operations

3.6.1 Description of the OI

There are three main strategies when planning the airline network configuration: hub-and-spoke, point-to-point, and multi-hub. The multi-hub is a variation on the hub-and-spoke, where two or more hubs are connected through a shared spoke route. The hub-and-spoke strategy structures the airline network around a hub (or multiple hubs). This allows airlines to serve more origin and destination (O-D) with the same number of flight departures, fleet and at lower total operating costs than in a complete point-to-point network. On the other hand, point-to-point strategies allow direct flights between airports, providing high convenience to passengers. For airlines, adopting a pure hub-and-spoke or point-to-point strategy may not always be the best answer because airlines try to optimize their entire network based on existing demand, operation costs, and sustainability constraints in a specific region. Consequently, the network might operate optimally under a mixed operation strategy [42]–[44].
There are a variety of strategies to reduce emissions produced in airline operations in terms of time horizon. In the long term, operating a new generation of aircraft redesigned for efficient fuel consumption is promising. In ClimOp, we mainly focus on short-term strategies that help airlines operate their current fleet more efficiently. In this OI, we aim to address airline SNP, considering fuel-saving practices that result in emissions reduction.

Airline network planning is a strategic decision and directly affects market share, operating cost, and passenger demand. Currently, airline networks are designed based on DOC and demand capturing intentions. These objectives are contributing to airline revenue but not necessarily efficient in fuel consumption. There would be a trade-off between airline total revenue maximization and fuel efficiency when designing an airline network. Airlines tend to have greener operations and networks concerning fuel consumption and emission production. They may need to sacrifice a part of their revenue, which may not be desirable for airline stakeholders.

3.6.2 Description of the assessment process

SNP is a long-term decision that usually does not change in periods less than a quarter or so. Mixed-integer programming (MIP) is commonly used in the literature of airline network modelling [45]. The shortcoming of this modeling method is its computational complexity in large scale and real-world applications. Heuristic approaches are then applied to find a reasonably good solution for those models. We aim to develop a multi-agent system (MAS) that consists of specialized agents to generate a strategic airline network. Agents will decide on which route to operate based on the demand flow between each origin-destination pair, and the operational constraints. The contribution is to maximize the demand served with minimum possible fuel consumption.

A MAS is, typically, a software system composed of multiple interacting intelligent agents within an environment [46]. The environment can be both computational and physical. It can be open or closed, i.e., an environment where the agents can enter and leave freely, or not, respectively. Our aiming model is representing the airline planning department. Each specialized agent is responsible for optimizing a part of the entire strategic plan. Local plans are then merged through a coordination process. In the plan merging stage, agents are trying to maximize the total utility while satisfying the constraints.

In contrast to models that just consider cost-related objectives, we will address fuel efficiency in SNP and climate effects due to emissions. Several KPIs are related to this problem and can capture the modeling efficiency. Airline expenses, DOC, emissions, and aircraft utilization are KPIs that we will use to show the solution quality.

Considering real-world constraints may limit the proposed strategies. Using MAS-modeling approaches would represent more realistic constraints than what we can see in MIP. We can also capture the airline operation's emergent behavior in the MAS models when new strategies are adopted. Capturing the emergent behavior of the system makes this approach a promising what-if analysis tool for airlines.

Emergent behavior would also represent the effect of airline network planning strategies on air traffic management. Other KPIs as network traffic concentration and network connectivity will be then possible to be addressed.

To calculate each flight's emissions and their effects on climate, we need to use a coupled optimization model with an external emission and climate effects calculation model. There could be pre-calculated flight legs and their alternative airports summarized in a table. The emission calculator model estimates the corresponding emissions based on the input flight legs table, a so-called offline configuration. SNP and flight emission and performance models can also run in parallel structure. The model configuration to run these two models simultaneously will be investigated further in the next deliverables. The design in connecting the optimization and aircraft performance and emission model for this OI is similar to the intermediate stop-over. The difference is in the optimization model itself. Still, the general setup is the same and will be developed in a collaboration between TUD and DLR.

3.7 Climate-optimised intermediate stop-over

3.7.1 Description the OI

Fuel expenses are one of the main components of direct operational costs in an airline. Depending on aircraft type and the operating network, it may rise from 20% up to 70% of the direct operation cost (DOC) [47]. One promising strategy in fuel consumption reduction is the concept of intermediate stop-over (ISO). The purpose of ISO is to find the best alternative among airport(s) within a reasonable distance of the actual direct flight path for refuelling. Refuelling the aircraft provides the benefit that the aircraft can take-off with a significantly reduced amount of fuel (and hence weight), which in turn reduces the "fuel for fuel", leading to an increase in fuel efficiency. Numerous modelling approaches have been suggested in the studies of airline operations and network management. The previous research on the topic was mainly focused on cost concerns [48]. Different combinations of costs, including direct operational cost, crew, maintenance, navigation and landing, were considered. In addition, some of the previous studies proposed advanced models to better estimate the flight performance, to model the wind effects [49], and to assess the potential climate impact [50].

Green aviation is a dominant trend in air transport research. Adapting green aviation strategies in the aviation industry leads airlines to pay even more attention to the environmental effects than the cost of their operations. By modelling this operational improvement, we aim to address climate effects produced by flight emissions, as well as cost-related objectives in airline operation optimizations. The inclusion of climate effect consideration at an airline level, when optimizing the airline network considering ISO options, is the core contribution of this research. One aspect would be the determination of a climate-optimized ISO network topology, i.e., selecting the refuelling airport not solely based on fuel or cost considerations but also including the climate impact.

Airlines can use this OI to improve their operating costs, eventually reducing their emissions and climate impacts simultaneously. This OI can also represent a trade-off between emissions and expenses based on available alternatives airports for refuelling in each flight leg. ISO could generate some new markets for airlines with a short to middle range fleet and use their current fleet to fly to far destinations. On the other hand, ISO increases flight time, which has an undesired effect on customer satisfaction and passenger demand. Aircraft utilization and depreciation are also affected in this type of operation, which should be considered in the modelling. Another stakeholder affected by ISO is the airport operator. Depending on the location of an airport, studies have shown that there will be a significantly increased demand for landings and take-offs, and available fuel at some highly affected airports. This may be conflicting with available infrastructure and capacity. Moreover, residents near those relevant airports will be affected by the increasing number of aircraft movements in terms of noise and Local Air Quality (LAQ) issues.

3.7.2 Description of the assessment process

There are two main approaches in modeling ISO in the literature [47]–[49]. Simulation-based methods were the first ones to find alternative airports and finally choose one with the best results. Secondly, mathematical programming optimizations were proposed to generate a more accurate analysis at the expense of more computation time. We aim to develop a multi-agent model to address this OI. The model is based on specialized agents. Each agent acts as a local optimizer that tries to solve a partial network problem locally. The local agents then coordinate their answers with each other until the convergence is reached. There will be one cost and also one climate

impact minimization objective to be optimized in this model. The optimization will be subjected to available airports with a pre-defined distance of direct flight path and related local costs.
The costs related to each alternative airport should be summarized in the cost matrix and will be determined based on available studies. Emissions and their respective impact on climate associated with each flight path is another crucial factor in the model. To calculate each flight's impact, we plan to apply a modeling chain established within DLR. Reduced emission profiles as part of the GRIDLAB tool can be used to efficiently determine the 3D emission distribution of a particular flight option. This can then be evaluated with respect to an appropriate climate metric by the climate response model AirClim [13], [51]. There could also be pre-calculated flight legs and their alternative airports saved in a lookup table, summarizing all possible options. A technical solution needs to be found to link proprietary tools from TUD and ITU (network optimization) and DLR (trajectory, emissions, climate impact) and to nest the mission level simulation into the network optimization; this could e.g., be done with a simulation environment, such as the Remote Component Environment (RCE) developed by DLR [52], which allows the creation of simulation/optimization chains, which are executed in a dislocated manner. The emission model will run an offline routine to calculate emissions of each flight leg.

Modelling and analysis of ISO operation show promising potential in saving airlines operational costs as well as the total operation climate effect. The model developed in this section should be evaluated by the cost and emission-related KPIs listed in D1.1 [37]. Namely, DOC, CO_2 emission and non-CO_2 emissions are KPIs that will be measured to make this OI comparable with other existing approaches. To implement this OI, considering possible effects on each O-D demand is a crucial requirement. The counter effect of a decrease in demand can be more than the cost saved by ISO. Modeling ISO at the airline level can help capture a more holistic view of this strategy's effects on the entire network. The adverse effects to residents near affected airports, e.g. due to noise and LAQ, may be qualitatively analysed based on the change in aircraft movements. Alternatively, a more detailed analysis with respective noise and LAQ models could be done for selected critical airports. This will be further investigated in WP2.

3.8 Single engine taxiing / E-taxi (tow truck or tug wheel) and hybrid taxi

3.8.1 Description of the OI

Aircraft engines are relatively inefficient when operating on the ground. There are three main options for reducing the usage of engines on the ground: Single engine taxiing, electric taxiing and using a tow truck to tow the aircraft from the gate to the runway and vice versa. All these solutions have in common that they only make sense if taxi time as at least 5 minutes, as else the engine start-up and cool-down time will mean the engines will have to run anyway and thus no fuel or emissions will be saved.

Single engine taxiing, which is already common practice for some airlines, has a limited environmental impact. Whilst one engine is not used, the other engine often has to be used at a slightly higher thrust level. On average, the CO_2 levels are expected to be less, CO and particulate matter will be much less, and NO_x will be slightly higher. For the airline, asymmetric thrust can cause issues, especially in combination with heavy wind conditions. This limits the usability and might cause an increase in incident rates.

Electric taxiing, using an electric motor in the wheels, reduces fuel consumption significantly. The APU generally provides electrical power, so fossil fuel is still burned but at higher thermodynamic efficiency. Fuel consumption, CO_2, CO, and organic particles emission per movement will be lower. NOx emissions might be slightly higher. The device and installation add weight, which will lead to an increased fuel burn (and thus emissions) in flight. For airlines, it thus makes the most sense to install this on aircraft flying short distances to and from the airport with long taxi times and many flights per day. For airports, the impact is limited, as long as taxi times do not increase dramatically due to lower speed. Taxi speed can be low if the APU can supply only a limited amount of electrical power.

Towing reduces fuel consumption significantly. Currently, tow trucks are diesel-based, so some emissions still take place. All emissions are expected to be reduced significantly, and NO_x production can probably be limited. The implications for the airline are somewhat limited, though they will need to implement operating procedures. The airport, or airport contractor, will have to invest in and operate a fleet of tow trucks. Larger airports with more flights and larger taxi times will have more benefits from this system. How many and if all aircraft can be towed is a question of the diminishing return on investment for each additional tow truck. In general, flights flying long routes will have the most benefit. Some limitations are the towing force the tow truck can apply to the nose gear and if the tow truck has enough traction (i.e., weight on wheels), which may limit the speed. There is also the operational challenge of the return flow of tow trucks between the terminal and the runways.

A hybrid solution, using a tug wheel with a tow truck, means the aircraft can use the electrical power from the tow trucks combined with the traction of the tug wheel and speed up the taxi speed without adding significant weight to the aircraft. This could be a solution at very large airports where the taxi speed is critical for departure sequencing. It is technically more complex with the power coupling and off course, causes more logistical challenges with both needing equipment available on the aircraft and the airport [53]–[55].

3.8.2 Description of the assessment process

Analyzing the methods of reducing taxi emissions requires three main sets of data, including the distributions of taxi times per airport, a worldwide flight schedule, and the ICAO engine emissions for different engine settings during taxi. The main aim for all OI's is to determine if and where (in term of airports or flights) they would be effective and quantify the costs and benefits.

For single-engine taxiing, the most effective way to analyse the impact on emissions is to calculate the time all engines need to be running on taxi in and out for engine cool down and warm up, calculate the additional thrust required from the single engine during taxi and the corresponding change in emissions per unit of time. Using the taxi time distribution at an airport, this will then result in a distribution in the change in emissions. Additionally, for some airport, assessments may be made to determine the availability of single engine taxi in combination with wind and slippery pavement conditions, which may limit usability.

For electric taxiing, additional to the assessment done for single engine taxiing, additional fuel consumption due to added weight must also be taken into account during flight, and the great circle distance can be computed with the flight schedule. It will initially be assumed that the fuel consumption and emissions will increase linearly with the empty weight (using the Breguet range equation) though later, the effect of lower cruise levels might be examined as well. It will also be assessed which are the most promising flights, airlines, and aircraft to implement this system on.

For towing, initially only the taxi times, with a deduction for engine warm-up and cool-down times, and aircraft type dependent emissions will be taken into account to determine the distribution of savings of towing per aircraft type and per airport. Both diesel and electrical tow trucks will be considered. Later, we will also try to address the marginal fuel and emissions saving per towing vehicle available at the most important airports taking into account the flight schedule.

For the hybrid system, the analysis for towing and electric will be combined with a lower additional weight penalty for the aircraft.

All KPIs will be determined in kg CO_2, CO, particulate matter, and NO_x savings per operation and the maximum total savings worldwide. For all options, a (rough) cost estimation will be made with a resulting cost per unit of emissions saved, including a sensitivity analysis. The implementability will be evaluated by interviews with airport and airline operators.

3.9 Promoting climate-friendly flight operations

3.9.1 Description of the OI

The non-CO_2 and CO_2 effects of aviation can effectively be mitigated by limiting "climate-unfriendly" flight operations. By imposing climate friendlier flight procedures on specific flight segments or re-routing above, below, or around climate-sensitive areas, "climate-unfriendly" flight operations are limited, and the overall climate impact is reduced. This OI is closely related to the OI described in Chapter 3.4: Climate-optimised flight planning, which concerns the operational aspects focused on the aircraft trajectories of climate-optimised flight, whereas the OI discussed in this chapter focuses on the regulatory means to promote climate friendly operations. Combining the price-based concept of Climate-Charged Airspaces (CCA, see [6] Section 2.11) with mechanisms to promote climate friendly flight (see [6] Section 5.1) through a market-based mechanism, assures a level playing field between stakeholders, while still optimising for climate optimal flight operations.

Limiting flight operations that are "climate-unfriendly" includes trade-offs between the CO_2 and non-CO_2 climate impacts. As this OI focuses directly on the mitigation of both non-CO_2 and CO_2 climate impact, dependent on total fuel burn, location, and time of emissions, it is expected that this OI has a large potential for the reduction of climate impact.

It is expected that national and supranational regulatory bodies will have to take measures to implement this OI. The most natural and effective measure to prevent "climate-unfriendly" flight operations as far as possible is to instruct ATM accordingly. However, the effect of other measures such as incentives/charges and guidelines for "climate-friendly" flight operations will also be assessed. ATM will need to facilitate this OI, and airlines and OEM's need to act and possibly invest in equipment to successfully implement this OI. Passengers will possibly experience longer travel times (due to detouring), and residents near airports might experience a change in operations in the Terminal Manoeuvring Area (TMA). Estimating the overall effects in terms of Local Air Quality (LAQ) and Quality of Life (QoL) requires additional research. While LAQ and QoL is not the focus of the ClimOP project, these factors will be taken into account for the final trade off and implementability of the OI. The general public will enjoy a positive impact on the climate and Quality of Life.

Advantages/disadvantages may favour/disfavour its implementation

This OI will need new technologies and methods to assess the climate sensitivity of airspaces and monitor this, which will require investments for appropriate equipment. This will need some sort of restructuring of airspace in climate sensitive area allocation, which might intensify ATM activities. It should also be checked whether there are any loopholes for stakeholders to avoid the extra charges/costs associated with this OI, which might actually result in a negative climate impact.

Once this OI is implemented, fuel use may increase, and thus CO_2 emissions may increase. Even though this might be outweighed by the decrease in non-CO_2 climate impacts, it may be disadvantageous in terms of CO_2 trading systems/caps.

However, as this OI will aim to limit "climate-unfriendly" flight operations, airlines could be motivated to invest in aircraft that are equipped for climate friendlier performance, both in terms of CO_2 and non-CO_2 climate impact performance. This could stimulate fleet renewal, causing a secondary (long term) positive impact.

3.9.2 Description of the assessment process

Determining the climate impact of this OI will be done by comparing different scenarios with, for example, different levels of avoiding climate sensitive areas, and different altitude levels, and different aircraft performance parameters. To assess the trade-off of climate impact between CO_2 and non-CO_2 emissions, important factors to be taken into account in the scenarios are different locations, altitudes and atmospheric conditions. Variables and impacts that will be compared, are:

- Fuel consumption (K3)
- Non-CO_2 emissions in climate sensitive areas and outside climate sensitive areas → related climate impact (related ATR20 and ATR100 – K1.1 & K1.2).
- CO_2 emissions and related ATR20 and ATR100 (K1.1 & K1.2).

To assess the climate impact of this OI, the specific emissions of the scenario's need to be available and analysed in a chemistry transport model or general circulation model. To this end, also background concentrations and weather-related data need to be available over an extended period of years.

This OI is considered as an extension of the "Climate-optimised flight planning" OI (Sect. 3.4) and will therefore take the outputs of the OI discussed in 3.4 partly as input for its assessment. However, the implementation of "Promoting climate-friendly operations" takes into account regulatory incentives, which triggers different stakeholder responses and influences different market based mechanisms. Therefore, this OI is aimed at exploring further options rather than rerouting, such as engine settings in climate-sensitive areas. The climate assessment, including CO_2 and non-CO_2 effects, is based on the modelling tools described in Sect. 3.4. More precisely, these include the EMAC earth-system model [56] with its components AirTraf [57], ACCF [33] and RAD [34]. AirTraf is used to optimise flight traffic based on weather conditions. ACCF estimates the climate impact of an aviation emission based on the local weather conditions. RAD simulates radiative transfer and is exploited to calculate K48. Sect. 3.4 of this document elaborates on a detailed description of the model hierarchy.

One of the remaining open questions of the described assessment strategy is how to compute the impact on climate over the long-time scale (e.g., ATR100). To this end, a specific study on the effect of changes in the climate regimes on the restriction strategies will be implemented. Special attention is given to the effect of this OI in reducing contrails formation. Contrails have the greatest potential of reducing the climate impact of aviation [31]. Concerning this OI, they are the main driver for the changes in the air traffic routing. The time and space analysis of the areas where the likelihood of contrail formation is particularly high is performed on the basis of the ECMWF Reanalysis products ERA 5. This preliminary study will create a baseline to compare the climate projections of the 5th phase Coupled Model Intercomparison Project (CMIP5). This second step will assess the viability of such this OI in view of climate change. The variation of the climate restricted or charged airspaces in the upcoming 10 years will be analysed by taking into account the uncertainties in the predictions. Furthermore, seasonal forecasts will be considered to explore the potential of this innovative tool for the mid-term planning of these regions.

Outline of the assessment of the effect on the stakeholders

The impact on stakeholders is related to the stakeholder's responsibility and involvement (owning, acting, responding). The impact of this OI will be assessed through KPI's related to the different stakeholders.

The gains and burdens of the **airlines** will be assessed through operating costs (fuel – K3, crew costs, maintenance costs – K5), aircraft operation time (K6), route efficiency (K7), and network &

flight planning (K13, K16). Aircraft utilisation (K17) may be affected if frequent noticeable flight time increases or reductions occur, which may affect airline revenue.

For **passengers**, the impact of this OI will be measured in terms of travel time (K33) and ticket costs, as the charges could be calculated through to the ticket costs.

The impact experienced by **ATM** will be assessed through the number of movements (K23) and airspace capacity (K2). The workload of ATM may also increase with the introduction of CCA's, as well as the workload of pilots who will have to perform the required flight operations. This, however, needs to be assessed properly through a Human Performance Assessment (cf. also [37]).

In order to determine the values for these KPI's, a combination of numerical models and interviews with stakeholders can be used. With numerical models, cost-related parameters, and parameters such as flight time, route efficiency, and movements can be calculated.

It is important to do the assessment for an entire airspace portion containing numerous aircrafts (different degrees of airspace congestion) – as the main effect is the additional congestion caused by reducing the airspace capacity if flights are diverted out of certain climate-sensitive areas.

Through stakeholder consultations, the involvement and commitment of operational stakeholders can be assessed, which will reflect on the KPI's that will be evaluated as well.

Outline for the evaluation of the feasibility and "implementability" of the OI

This depends on the scale on which the OI's will be implemented, as this involves different standards, infrastructure, capacities, maturity, willingness, and commitment levels of stakeholders and costs.
The feasibility of this OI should be evaluated based on the KPIs and overall impact on climate. While doing so, the aforementioned variability with respect to different standards should be taken into account. Furthermore, through stakeholder feedback sessions, insights on stakeholder behaviour, decision making, and capability and capacity to implement this OI will be tested.

If the OI is implemented without introducing proper regulations, ATC will determine the route that will be flown by airlines, which affects the charges that airlines will face while flying through CCA's. These burdens, however, need to be fairly distributed over the stakeholders, such that not all burdens will befall upon one stakeholder. This needs to be assessed in more detail and will be further assessed in Work Package 3. It would be valuable to discuss these options for implementability through stakeholder feedback sessions. Insights on stakeholder behaviour, decision making, and capability and capacity to implement this OI will be tested.

3.10 Electrification of ground vehicles and operations [SEA]

3.10.1 Airports electric mobility – description of the OI

The main source of direct emissions (scope 1 emissions[2]) for an airport is determined by the consumption of diesel and gasoline of its fleet of land transport vehicles, both Land Side and Air Side [58]. The fleet can be divided into 5 macro categories of vehicles: Automotive, Trucks, Buses, Airport Specific vehicles and Winter Snow vehicles.

The conversion of the airport fleet from vehicles with internal combustion engines to electric traction vehicles completely eliminates the production of carbon dioxide and NOx on site, thus reducing the greenhouse effect and improving the local air quality.

The main stakeholders involved in the replacement of traditional vehicles are the direct users of these vehicles.
The operational airport staff (e.g. drivers, de-icers, etc.), will have to adapt and, in some cases, even be trained on the use of new technology vehicles, brought by the transition to electric.

The conversion of the fleet implies the analysis of the quantity of vehicles effectively needed, besides the analysis on their usage and their storage locations (defined according to the charging points), thus providing the possibility of optimizing the entire fleet, up to the point of reducing the number of units, introducing or implementing alternative methods of use (e.g. car sharing) and reviewing the policies for the use of vehicles.

The main advantage, in addition to the elimination of direct emissions of scope 1 and consequent improvement of air quality, is represented by the disengagement from the use of energy vectors deriving from fossil sources with consequent savings in the costs of refueling and maintenance of the vehicles. It is also worth considering the reputational gain as today the attention on environmental issues (and especially on sustainable mobility) is very high.

The major disadvantage is represented by the significant initial investment cost for the purchase of electric vehicles and especially for the construction of the infrastructure necessary for the charging points of the vehicles.
A further point of attention concerns rapid technological development in progress which risks making some choices obsolete ahead of time with respect to what was planned

3.10.2 Description of the assessment process

The use of vehicles with internal combustion engines, which consume diesel and petrol, generates CO_2 and NOx emissions: these are the main greenhouse gases, aggravating global warming. As highlighted in the previous chapter, replacing the use of endothermic motor vehicles with electric traction vehicles means eliminating climate-changing gas emissions on site and significantly reducing global emissions generated by the production of electricity. If the electricity used to recharge the batteries is generated from renewable sources, then the use of electric vehicles also makes it possible to cancel global emissions.

[2] Direct emissions are emissions from sources that are owned and controlled by the reporting company. These emissions are considered scope 1 and include fuel combustion on site such as gas boilers and fleet vehicles.

The analysis of consumption and corresponding emissions must be carried out by taking into consideration all types of vehicles used within the airport. For each vehicle the following elements must be evaluated:

- the type of use,
- the way it is used,
- equipped auxiliary equipment and their energy consumption,
- the daily mileage
- the existence or not of the electric alternative.

To assess in detail the actual impact of the OI, it is possible to define specific consumption per km [liters / km] and, by applying the appropriate emission factors, consequent emissions per km [g / km of CO_2].

In global terms, the reduction of emissions in one year [ton CO_2 / year] can be quantified by defining an annual consumption baseline and calculating the liters of gasoline and diesel fuel saved per year, using the appropriate emission factors.

The method used to define a fuel consumption baseline, performed before the fleet conversion to electric starts, is of the arithmetic type and consists of calculating the average, for example, of the previous three years of the annual consumption of diesel and petrol, relating to the fleet of vehicles replaced. This resulting average consumption data, multiplied by the appropriate emission factors, provides the reference tons of CO_2 equivalent avoided in the period analyzed. To assess the actual annual reduction of direct emissions, it is necessary to measure the annual electricity consumption of all recharging points and, using the appropriate emission factor, calculate global emissions. The difference between baseline emissions and annual global emissions represents the actual CO_2 saved in the reference year.

Besides the emissions reduction, another important effect of using electric vehicles instead of traditional ones with internal combustion engines, is the reduction of refueling costs and the reduction of maintenance costs. As for the evaluation of emissions savings, it is possible to calculate the usage costs [€ / Km], the refueling costs [Km / kWh and € / kWh], and compare them with the corresponding known management costs of the traditional car fleet.

Airport operations are characterized by a great variety of complementary activities that ensure all the necessary services for the proper management of aircraft operations, before approach and landing, during the turnaround and even after take-off. In addition, the diversification of services offered by airport operators has developed in recent years business sectors unrelated to aviation operations. All these countless activities, which are carried out simultaneously every day, involve various types of vehicles, from simple cars to special vehicles for aeronautical operations.
In the transition to electric vehicles, it is, therefore, necessary to carefully evaluate the electric alternatives of all operating vehicles, also deciding to postpone the passage of some categories of vehicles if current technologies are not yet fully mature.

The major obstacle to implementing this OI is undoubtedly the high initial cost for the purchase of the vehicle fleet and above all for the construction of the substantial infrastructure necessary for the installation of the charging points.

In evaluating the long-term effects, in addition to the initial investment cost, management savings, and the use of any incentives must be considered. Above all, the development of technologies and socio-economic conditions must be carefully evaluated because, in the immediate future, they could also make the maintenance of fleets powered by endothermic engines economically disadvantageous, for example in case tax mechanisms aimed at penalizing the consumption of fossil fuels were introduced.

3.11 Upgrade of the airport infrastructure according to energy efficient criteria

3.11.1 Description of the OI

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.). For instance, the Spanish airports consumed up to 3,236,086 GJ in electricity and 241,565 GJ from fuel in 2014 alone [59]. The main energy consumption in airport buildings and plants, during their operational life, are:

- space and water heating;
- central air conditioning/cooling;
- equipment and lighting;
- electricity consumption by electric motors.

The improvements in the infrastructure are expected to contribute to the reduction of the energy consumption of airports. According to Akyüz et al. [60], around "70% of the energy consumed in airport terminal buildings is used for heating, cooling and air conditioning purposes". This energy consumption highly depends on climate conditions. Climate conditions, such as temperature, humidity, irradiation, and wind direction and speed, are key factors of energy consumption in terminal buildings, focused mainly on the needs of heating and cooling systems and lighting [61]. Therefore, there is a tight connection between the climate conditions and energy efficiency. In fact, the energy need depends on the climate conditions that might change in the future. At the same time, enhancing energy efficiency will reduce the emission and the impact of airports on climate.

Apart from airports, the stakeholders involved in this OI are institutional bodies and energy providers as well as passengers. The main disadvantage for airports is the initial investment needed to upgrade the existing infrastructure, constituting the main limit in the implementabililty of this OI. From a technological perspective, the engineering advances in the field of energy efficiency have been huge and the OI is fully feasible. However, the initial investment should return in 5-10 years thanks to the direct reduction in the cost for energy supply [62]. Moreover, the airport greatly benefits from an improvement in its reputation, in case the upgrade is communicated adequately to the public.

3.11.2 Description of the assessment process

The assessment of the OI will focus on the following KPIs:

- K51: Annual electricity consumption per unit of volume
- K52: Annual thermal energy consumption per volume unit
- K53: Annual electricity consumption per traffic unit
- K54: Annual thermal energy consumption per traffic unit
- K59: Social acceptance

The analysis will start with a literature analysis of the most effective options for energy efficiency at airport level, with particular attention to the cost-benefit analysis of the different options. In the second step, this information will be considered in the context of climate change. The climate projections available through the 5th Coupled Model Intercomparison Project (CMIP5) will be exploited and compared to the baseline corresponding to the present conditions based on the ECMWF re-analysis products ERA5. The OI assessment will investigate how the energy demand will change in the upcoming decades and will identify the regions where the climate conditions will change so much that the present infrastructure will soon become obsolete. To this end, the ClimOp consortium will focus on the atmospheric conditions that impact the energy need of airports the most: temperature, humidity, irradiation, and wind direction and speed.

The OI assessment will include a deeper analysis of a specific case study based on SEA Milan. The possibility to directly cooperate with the airport operators will enable to test the hypothesis formulated in the general analysis. It will also simplify the estimate of the quantitative KPIs (K51-54), and possibly the qualitative KPI (K59) on the basis of datasets (e.g. [63]) and other documentation[3]. The latter will be investigated with surveys with passengers/citizens and interviews with airport stakeholders to understand their interest and sensitivity to this OI.

3 http://www.seamilano.eu/it/archive/dichiarazione-consolidata-carattere-finanziario-31-dicembre-2019

4. Conclusion and future work

Work package 1 consists of five tasks. The first three tasks are all interconnected within WP1: the outputs of tasks T1.1 and T1.2 are combined in Task T1.3 which provides a preliminary assessment of the potential benefits and disadvantages of each of the operational improvements identified in T1.2, based on the KPIs identified in T1.1.

The tasks T1.4 and T1.5 are preparatory for the study to be conducted within WP2 and, finally, in WP3. The present deliverable addresses the fourth task of WP1, T1.4: “Selection and review of operational improvements to be investigated”. The goal of T1.4 is the selection of the first round of OIs, based on the preliminary assessment conducted in Task T1.3, in terms of climate impact mitigation, also considering the non-climate KPIs to account for stakeholders’ interests, and, as such, provide a comprehensive list of potential improvements

The 11 OIs selected in T1.4 will be investigated in T2.3: “Iterative climate impact assessment”, in this task, ending in Month 24, the impact of different OIs, or combinations of OIs, on the climate and on the relevant aviation stakeholders will be quantified with different modelling tools combining simulation of air traffic and climate impact.

The results of T2.3 are used to refine the list of OIs in WP1 and create a second round of OIs in Task T1.5: “Second iteration for the identification, assessment and selection of operational improvements”. In this task, ending in Month 25, a detailed analysis of the first set of OIs selected in T1.4 will be performed, based on the feedback from different stakeholders and the knowledge gained in WP2 and, partially, in WP3.

T1.5 is the basis for T2.4: ”Uncertainty in climate impact assessment due to model variability”, ending in month 29 and reported in the document D2.4: “Report on the climate impact of the second set of operational improvement options”

The tasks described above constitute the basis of WP3: “Selection and recommendation for the implementation of mitigation strategies” The activities in this WP, which starts in month 23 and ends in month 42, are carried out in two iterations: the first iteration concerns the first round of OIs selected in T1.4 and the second iteration concerns the second round of OIs re-considered in T1.5.

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Appendix A

A.1 Overview of models and databases

The following Tables Table ***4*** and Table ***5*** is a concise summary of the models and databases which have been mentioned in the previous sections and will eventually be used in the impact assessment of the OIs.

Table 4. List of models to be eventually adopted in the impact assessment of the OIs.

Name	Description
AOMAS	Airline operations multi-agent system (AOMAS) consists of specialized agents responsible for planning and scheduling in operation. This model will be used to evaluate the OIs in sections 3.6 and 3.7.
EMAC/AirTraf	AirTraf is an air traffic simulator coupled with ECHAM/MESSy Atmospheric Chemistry (EMAC) model. It considers local weather conditions to calculate flight trajectories for various purposes, e.g., cost optimal, climate optimal, etc. This model will be used to evaluate the OI in section 3.4.
TCM – Trajectory Calculation Module	Flight mission simulator, which computes four-dimensional (2D location, altitude, time) aircraft trajectories from lift-off to touch-down applying a kinetic mass-point model that provides simplified equations of motion known as Total Energy Model (TEM). It was developed for the purpose of modelling flight movements in a sufficient level of fidelity for environmental analyses and therefore does not capture aircraft dynamics.
TOM – Trajectory Optimisation Module	Estimation of continuously optimised aircraft trajectories based on an optimal control approach and the TEM. Aircraft's motion is described as temporal evolution of control variables (e.g. aircraft heading, thrust) and resulting state variables (e.g. position, mass, emissions). Optimised aircraft trajectories are determined by identifying a control input which minimises a cost functional which may be defined as weighted sum of direct operating costs, fuel burn, emissions and climate impact.
GRIDLAB **– Global Air Traffic Emission Distribution Laboratory**	Modelling system developed for the environmental analysis of new technologies and operational concepts for aviation. It is capable of calculating emission inventories capturing the use of these new technologies or operations, as it includes an emission model based on the Boeing Fuel Flow correlation method. Due to the integrated character of the tool modules are available that allow for the consideration of realistic operational boundary conditions, especially wind effects.
EMAC	EMAC is an open access and open source state-of-the art community Earth-System model based on the European Centre for Medium Range Weather Forecasts – Hamburg (ECHAM) climate model as part of the Modular Earth Submodel System (MESSy) Atmospheric Chemistry model. Sub-models describe tropospheric and middle atmosphere processes and their interaction with oceans, land and human influences.
EMAC/ATTILA	ATTILA is a submodel in the modular EMAC system, performing a Lagrangian trajectory calculations, and transport studies of e.g. aircraft emissions and impacts in the global model system.
EMAC/AirTraf	(please move text from further above here)

AirClim	The climate-chemistry response model AirClim combines results of detailed climate-chemistry models, with emission data to obtain time series of radiative forcings and temperature changes caused by these emissions. These climate-chemistry model results describe the impact of a local emission on the radiation budget, e.g. the change in contrail-cirrus radiative forcing due to air traffic, and eventually on the global mean near surface temperature.
Trajectory Generation Tool	The tool calculates the trajectories for given initial conditions and flight plans. It consists of an aircraft performance model based on BADA and a trajectory tracking layer, which generates the required control inputs to follow the trajectory between specified waypoints. The required flight plan for an aircraft is a set of waypoints in terms of latitude, longitude, and altitude. The tool also calculates the fuel consumptions during the flight that could be used to calculate the emissions.
Trajectory Optimization Tool	In this tool, the trajectory planning problem is transformed into an optimization problem to generate the optimal control inputs with regards to defined objectives. The dynamic constraints that come from an aircraft performance model, performance limits, and other restrictions are presented as the constraints of the optimization problem.
Airport-Centric Queuing Network Model	This model is used to simulate the delay propagation within an airport network by evaluating demands, airports' capacity limits, and distruptive events. Using this model, the impact of local delays and disturbances on the network can be evaluated. By this way, the the airport-centric capacity constraints could be considered during the evaluation processes of the related OIs.

Table 5. List of databases to be eventually adopted as data sources in the OI impact assessment.

Name	**Description**
BADA	EUROCONTROL’s Base of aircraft data (BADA) is a source of the best available aircraft performance reference data and enables users to realistically reproduce the geometric, kinematic and kinetic aspects of your aircraft’s behaviour over the entire operation flight envelope and in all phases of flight.
ERA5	Reanalyses combine past observations with models to generate consistent time series of multiple climate variables. Among them, ECMWF Re-Analysis product version 5 provides hourly estimates of a large number of atmospheric, land and oceanic climate variables. The data cover the Earth on a 30km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80km. The dataset is available from 1979 to within 5 days of real time
CMIP5	The results of the fifth phase of the Coupled Model Intercomparison Project (CMIP5) are collected in a soud database. They include long-term climate projections of several Global Circulation Models (GCMs) and for different Representative Concentration Pathways (RCPs), which are greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its Fifth Assessment Report (AR5).
SEAS5	SEAS5 is the ECMWF’s seasonal forecasting system vetion 5. Atmospheric predictions of the upcoming 6 months are provided on the

	13th day at 12 UTC of every month. The dataset includes a multi-model ensemble prediction entailing different simulations for each model, differing only in the initial conditions.
Assaeroporti statistics	This dataset with statistics on 42 airports in Italy is provided by the Italian association of airports. The dataset includes statistics on air traffic and passengers.
ALLFT+ Dataset	The dataset contains the historical traffic data of Pan-European air traffic. The dataset mainly consists of flight plan information. The high-level information about a flight includes departure aerodrome, destination aerodrome, departure time, aircraft identification, flight rules, type of flight, type of aircraft, radio communication, navigation and approach aid equipment and capabilities, and surveillance equipment.