Climate assessment of innovative mitigation strategies towards operational improvements in aviation

D1.3 – Report on the assessment of operational improvements against identified KPIs

Document author(s) and Company - **A. Tedeschi (DBL), C. Abate (DBL), Elena Branchini (SEA), Luca Bissossero (SEA), Mattia Grampella (SEA), Davide Canuti (SEA), K. Sutopo (NLR), J. Middel (NLR), B. Ohlenforst (NLR), J. Derei (NLR), F. Linke (DLR), S. Matthes (DLR), C. Weder (DLR), B. Başpinar (ITU), I. Ozkol (ITU), E. Koyuncu (ITU), V.S.V. Dhanisetty (TUD), M. Noorafza (TUD), F. Yin (TUD), P.V. Rao (TUD), S. Dal Gesso (AMIGO)**

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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).

1	deepblue	DEEP BLUE Srl (DBL) 00193 Roma, Italy www.dblue.it	Contact: Alessandra TEDESCHI Alessandra.tedeschi@dblue.it
2	nlr	KONINKLIJK NEDERLANDS LUCHT- EN RUIMTEVAARTCENTRUM (NLR) Anthony Fokkerweg 2 1059CM , Amsterdam, Netherlands	Contact: Barbara Ohlenforst barbara.ohlenforst@nlr.nl
3	TU Delft	TECHNISCHE UNIVERSITEIT DELFT (TU Delft) Stevinweg 1 2628 CN , Delft, Netherlands	Contact: Bruno F. Santos b.f.santos@tudelft.nl
4	DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV (DLR) Linder Hoehe 51147 , Koeln, Germany	Contact: Florian Linke Florian.Linke@dlr.de
5	Amigo CLIMATE CHANGE	AMIGO SRL (AMIGO) via Flaminia 48 00196 , ROMA Italy	Contact: Sara Dal Gesso sara.dalgesso@amigoclimate.com
6	İTÜ	ISTANBUL TEKNIK UNIVERSITESI (ITU) Ayazaga Kampusu 34469 , Maslak Istanbul Turkey	Contact: Ibrahim Ozkol ozkol@itu.edu.tr
7	IATA	IATA ESPANA SL SOCIEDAD UNIPERSONAL (IATA) Paseo de la Castellana 95, 5 28046 , Madrid, Spain	Contact: Thomas Roetger roetgert@iata.org
8	SEA Milan Airports	SOCIETA PER AZIONI ESERCIZI AEROPORTUALI SEA SPA (SEA) Aeroporto Linate 20090 , Segrate Italy	Contact: Elena Branchini elena.branchini@seamilano.eu

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			B. Başpinar (ITU) I. Ozkol (ITU) E. Koyuncu (ITU) V.S.V. Dhanisetty (TUD) M. Noorafza (TUD) F. Yin (TUD) P.V. Rao (TUD) S. Dal Gesso	Updates on Sections 2.1, 2.3, 2.4, 2.7, 2.9 Updates on Sections 1.3, 3.2, 3.5, 3.6, 4.3, 4.4, 6 Updates on Section 4.7
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			S. Matthes (DLR) C. Weder (DLR) B. Başpinar (ITU) I. Ozkol (ITU) E. Koyuncu (ITU) V.S.V. Dhanisetty (TUD) M. Noorafza (TUD) F. Yin (TUD) P.V. Rao (TUD) S. Dal Gesso	2.6, 2.8, 2.10, 2.11, 3.1, 3.4 Updates on Sections 2.1, 2.3, 2.4, 2.7, 2.9 Updates on Sections 1.3, 3.2, 3.5, 3.6, 4.3, 4.4, 6 Updates on Section 4.7
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Executive summary

The ClimOp project investigates, for the first time, in a sound research framework, which operational improvements do have a positive impact on climate, taking non-CO_2 effects into account. Subsequently, it will analyse and propose harmonised mitigation strategies that foster the implementation of these operational improvements. To this end, the ClimOp consortium builds on its knowledge and expertise covering the whole spectrum from aviation operations research as well as atmospheric science and consulting to airline and airport operations.

Deliverable D1.3 addresses the third task (T1.3) in the ClimOp project Work Package 1 (WP1), to provide a preliminary assessment of the potential benefits and disadvantages of each of the operational improvements identified in task T1.2, based on the KPIs identified in task T1.1. Deliverable D1.2 lists up to 44 operational improvements (OIs), brainstormed among the partners during the early phase of WP1. At the beginning of task T1.3, we collectively took the opportunity to prune or combine the initial OIs into a concise list that best suited the expertise of the contributors involved. As a result, D1.3 will provide an assessment of the following 25 OIs categorised into four groups:

Climate-optimised operation of the airline network

- Performance-Based Navigation for landing
- Continuous climb/descent operations
- Departure/arrival management extended to en-route airspace
- Free routing in high-complexity environment/flexible waypoints
- Formation flying
- Flying low and slow
- Optimal seperation minima
- Climate-optimised flight planning
- Wind/weather-optimal dynamical flight planning
- Climate-restricted airspaces
- Climate-charged airspaces

Climate-optimised trajectory

- Routing optimised for contrail (night) avoidance
- Climate-optimised intermediate stop-over
- Trade flight frequency for aircraft size
- Climate-optimised North-Atlantic Track System
- Strategic planning: merge/seperate flights; optimal hub-spokes/point-to-point operations

Operational and infrastructural measures on the ground

- Upgrade of the existing infrastructure according to energy efficiency criteria for the reduction of environmental impacts
- Volutary initiatives to reduce CO2 emissions
- E-taxi (tow truck or tug wheel) and hybrid taxi
- Single engine taxiing
- Electrification of ground vehicles and operations
- Implementation of a monitoring system for the atmospheric emissions
- Renewable energy produced at airport

Operational measures at regulatory level

- Limit "climate-unfriendly" aircraft operations
- Environmental scoring

Figure 1 – Operational improvements assessed in D1.3

Each OI has a dedicated chapter, including a description and impact of the OI, and OI's preliminary assessment. The reader will obtain an overview of the current qualitative and quantitative state of the OI using the KPIs form D1.1. Hence, identifying the work done so far on each strategy, and the gaps left to research. The findings of D1.3 will contribute to the next task in WP1, T1.4 – Selection and review of operational improvements to be investigated.

1. Introduction

1.1 ClimOp project

The aviation industry contributes to human-made emissions mostly by releasing carbon dioxide (CO_2), water vapour (H_2O), nitrogen oxides (NO_x), sulphur oxides (SO_x), soot and sulphate aerosols. In terms of the influence human activities as a whole have in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, that is the anthropogenic radiative forcing, the contribution from aviation has been estimated at slightly less than 5% [1]. Despite the sudden drop in air traffic caused by the Covid-19 crisis during the first two quarters of 2020 [2], the growth projections in air traffic by 3 – 4% per year suggest that the aviation impact on climate will significantly increase over the next decades unless effective counteractions are taken.

Under the coordination of the Air Transport Action Group (ATAG), the aviation sector has long committed to cut its emissions and implement mitigation strategies to reduce its impact on the environment and climate [3]. 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. While GreAT explores innovative, “climate-friendly” methods of air traffic management, ALTERNATE researches on new fuels less dependent on fossil sources and ACACIA aims at setting a new standard in the scientific understanding of the aviation contribution to climate change. The ClimOp project has a comprehensive approach that considers all the proposed operational improvements in the literature, identifies the most promising operational improvements to have a positive effect on climate, and assesses their impact on the aviation stakeholders.

In the first two-quarters 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. Over the course of the project, alternative sets of compatible OIs will 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, ClimOp will evaluate the impact of these OIs on airports, airlines, air navigation service providers (ANSP), manufacturers and passengers. As a result of this analysis that combines both a scientifically-sound research component and the stakeholders’ perspectives, 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. The strategy adopted to reach the specific objectives of the ClimOp projects are described in some detail in the deliverables D1.1 and D1.2 [4], [5].

1.2 Work package 1

Work package 1 (WP1) is devoted to determining the OIs that potentially mitigate the impact of aviation on climate. The first steps in this direction consisted in compiling an exhaustive inventory of all possible OIs that can be introduced, from the choice of ground equipment to changes in the allowed routes and specifically designed regulations to encourage climate-friendly practices [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 ensuring that requirements such as operation safety, practical feasibility, and long-term economical sustainability are taking into account in the analysis.

The activities of WP1 will continue with an analysis aimed at associating each OI with the most relevant KPIs that capture its consequences for the climate and the involved stakeholders. The results of this analysis are described in the present report. Subsequently, a preliminary, qualitative assessment will identify a selection of most-promising OIs for which a quantitative study will determine the climate impact mitigation potential (in the context of WP2). If this study 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 1.3 in the Project's context

The deliverable D1.3 "Report on the assessment of operational improvements against identified KPIs" provides a preliminary assessment of the potential benefits and disadvantages of the operational improvements identified in D1.2, based on the KPIs identified in D1.1. As a continuation of the work conducted in WP1, certain OIs were re-evaluated for relevance and similarity to other OIs. Where appropriate the some of the OIs mentioned in D1.2 have been merged together if the modelling techniques and strategies were same or similar. Additionally, any OIs that did not fit with the expertise of the partners within ClimOP have been dropped to ensure the efforts are placed on topics that we can assess to sufficient quality.

This report covers four different categories of OIs: Climate-optimised operation of the airline network (11 OIs), Climate-optimised trajectories (5 OIs), Operational and infrastructural measures on the ground (7 OIs), Operational measures at regulatory level (2 OIs). Each category of OIs has a dedicated chapter, and the preliminary assessment includes a description and impact of the proposed improvement strategy, the KPI evaluation based on literature and case studies, and summarized table of advantages and disadvantages. The purpose of this assessment is to identify the work done so far on a particular strategy, and the gaps left to research. Hence, the level of assessment may vary based on the novelty of the OI.

2. Climate-optimised operation of the airline network

This chapter is focused on the preliminary assessment of various OIs related to the airline network. There are in total 11 OIs being considered covering different flight phases through the entire flight missions, for instance, performance based navigation (PBN) for landing, continuous climb/descent operations (CCO/CDO), departure/arrival management extended to en-route airspace, free routing in the high-complexity ATM environment, flying low and slow, climate-optimized flight planning, etc. Some are already implemented (e.g. CCO/CDO), some could be implemented soon, and others require significant maturing of tools, methods and processes (e.g. climate-optimised flight planning) or even development and testing of basic concepts (e.g. formation flying). Each of the OIs is evaluated against KPIs, like fuel consumption, flight time, cost, climate impact (indicated by different metrics). Thereafter, the advantages and disadvantages related to various OIs are summarized.

The climate impact is composed of CO_2 emissions, which are directly proportional to fuel burn, and non-CO_2 emissions, which depend on flight altitude, humidity and many other parameters. For some OIs the benefit comes to a large extent from fuel burn reduction, i.e. CO_2 reduction. Non-CO_2 emissions are mentioned only if the OI has a specific influence on the parameters affecting non-CO_2 emissions (altitude, flight through contrail-formation areas, etc.). Noise and local air quality are additional important environmental aspects for the airport neighbourhood but are not part of the climate impact.

2.1 Performance-Based Navigations for landing

2.1.1 Description and impact of the OI

In the current sensor-specific navigation method, the ground-based navigation aids are used to develop airspace, Air Traffic Service (ATS) routes, instrument flight procedures, and obstacle clearance criteria. The concept of Performance-based Navigation (PBN) brings a paradigm shift in the aircraft's required navigation capability from sensor-based to performance-based. In the PBN concept, aircraft RNAV (Area Navigation) or RNP (Required Navigation Performance) system performance requirements are defined in terms of accuracy, integrity, continuity, and functionality when supported by the appropriate navigation aid (NAVAID) infrastructure [i]. A navigation specification is either an RNP specification or an RNAV specification. The main difference between an RNAV and RNP specification is that on-board performance monitoring and alerting system is a requirement for an RNP specification, while that is not a requirement for an RNAV specification. Conventional routes consist of airways that are constrained by ground NAVAIDs, whereas RNAV enables aircraft to fly on any desired route [ii]. Because of the on-board navigation capability, RNP allows crews to fly aircraft along a precise flight path with exceptional accuracy, and it provides the ability to determine aircraft position with both accuracy and integrity. Currently, the RNP system does not ensure the guidance to fly the Instrument Landing System (ILS) / Microwave Landing System (MLS) / Global Navigation Satellite System Landing System (GLS) procedure. Consequently, the PBN manual [i] does not include ILS/MLS/GLS precision approach and landing operations. Implementation of PBN for landing operations will extend the benefits of the concept to an additional flight phase. For this purpose, RNAV or RNP procedures should be designed for landing to specific runways, and aircraft should be equipped with the necessary onboard systems to implement the corresponding navigation application. By this way, aircraft can use smoother and shorter horizontal routes for landing.

Several stakeholders are affected by the PBN concept for landing. Each stakeholder focuses on a particular aspect of this concept, and each one is affected by this concept differently. Airspace planners and procedure designers are responsible for route spacing, aircraft separation minima, and procedure design. Airworthiness and regulatory authorities guarantee that the operational requirements are satisfied by aircraft and aircrew. Similarly, operators/users are compelled to realize the operational requirements and impact of any required changes for equipage and personnel training. Controllers and pilots are the real-time performers of this concept.

Aircraft must be equipped with an RNAV or RNP system able to support the desired navigation application. An RNAV or RNP system should also be compliant with a set of functional requirements and have a navigation database. The Country where the Operator is registered must ensure the certification and approval of the aircraft to operate in accordance with the navigation specification prescribed for operations in the airspace, along an ATS route or instrument procedure. According to operational requirements and navigation specifications, operators/users need to make determinations with respect to their equipage and personnel training. As end-users of the PBN concept, controllers and pilots are included in the navigation application, which contains the navigation specification and the NAVAID infrastructure. Pilots must receive the required training, briefings, and guidance material for safe operation. For pilots, the main benefits of an RNAV or RNP system are reduced cockpit workload and increased safety because of the navigation function performed by highly accurate and sophisticated on-board equipment. From the standpoint of controllers, the main advantage of an RNAV or RNP system is that ATS routes can be straightened because it is unnecessary to use the routes that pass over locations marked by conventional NAVAIDs. Another benefit is that RNAV-based arrival and departure routes can complement, and even replace, radar vectoring, thereby reducing approach and departure controller workload.

The PBN concept is developed to satisfy explicit and implicit strategic objectives such as improved or maintained safety, increased air traffic capacity, improved operational efficiency, more accurate flight paths, and mitigation of environmental impact. Besides, it can reduce the cost of operational inefficiencies for landing, such as multiple step-down and circling approaches.

2.1.2 Preliminary assessment of the OI

Table 1: KPIs related to PBN for landing. The research on PBN for landing is limited. Further analysis will be conducted in ClimOp to assess the impact of OI on relevant KPIs.

KPI	Unit	Value	References
K1.1 ATR20, K1.2 ATR100	K or °C	TBD	
K2.1 CO_2	Kg	TBD	
K2.2 NO_x	Kg	TBD	
K2.3 H_2O	Kg	TBD	
K2.4 PM	Kg	TBD	
K3 Fuel flow	Kg	TBD	
K4 LTO cycle	cycles per unit time	TBD	
K11.1, K11.2 Accident rate – ground and TMA	% change in count of events / frequency of occurrence per flight hour	TBD	
K21.1 On-time performance	Delay in time per event	TBD	
K25.1 Routing efficiency	Added flight distance or time	TBD	
K26.3 Airport capacity	Movements per unit time for runways	TBD	
K27.1 Airport traffic	Movements per unit time	TBD	
K33 Travel time	Time (per event of average over unit time)	TBD	
K38 Airline expense, K39 Airline revenue	CASK, RASK	TBD	

Table 2: Advantages and disadvantages of Performance-based Navigations for landing

Advantages	Disadvantages
Reduces the need to maintain sensor-specific routes and procedures	Increases cost because of extra pilot training
Improves operational efficiency	Increases cost because of on-board RNAV/RNP equipment
Greater navigational precision and accuracy	Increases cost because of new landing procedure names, definitions, and charts
Reduces step-down and circling approaches	
Reduces environmental impact	
Improves safety	
Increases airspace capacity	
Reduces missed approaches	

2.1.3 References

[i] ICAO. *Doc 9613, Performance-based Navigation (PBN) Manual*, 2008

[ii] EUROCONTROL, *Introducing Performance Based Navigation (PBN) and Advanced RNP (A-RNP)*, 2013.

2.2 Continuous climb/descent operations

2.2.1 Description and impact of the OI

The variation of present-day descent operations can be described as a mix of continuous (CDO) and stepped approaches. The latter consists of alternating descent and level segments from top of descent (ToD) until touchdown. During the level flight (at constant speed) aircraft need to apply higher thrust in order to maintain speed and altitude, causing increased fuel flow and noise emissions. Compared to the stepped approach, CDO is more efficient because total fuel burn (and noise emissions) during the descent phase is minimised by avoiding level flight. While the stepped approach gives ATC high controllability of its airspace, with CDO, it loses some degrees of freedom and thereby increases workload, especially in high traffic density environments [i]. To alleviate these problems, different solutions have been proposed and/or implemented like fixed approaches, point merge, interval management, etc. A 2018 EUROCONTROL study found that, from ECAC member states, 24% of flights applied CDO from ToD and 41% from FL75 [ii].

In the case of climb operations, most flights from ECAC member states already follow continuous climb operations (CCO) (between flight level 100 and top-of-climb on 74% to 94% of all flights) [ii]. This means that most flights can climb uninterrupted, not levelling off at non-optimal altitudes, and thus minimising fuel burn and potentially noise (given the lay-out and habitation of the surrounding area). Airspace with constraints due to interfering operation of other aircraft can result in a higher amount of level flight procedures. Also, airport ATM rules often specify which climb procedure (e.g. NADP-1 or NADP-2) must be followed by their pilots. This and the applied thrust (reduction) are, within CCO operations, factors that determine the impacts due to CO_2, non- CO_2 and noise emissions. For further details on this OI, please refer to D1.2 [v].

Impact on Climate

Climate impact due to climb and descent operations may be minimised by avoidance of level-flight segments. The reduction potential of CDO/CCO on emissions (CO_2, non- CO_2 and noise) is strongly dependent on current operational practices. Dependencies are, for example: level-flight altitude and segment length, climb/descent angle, gear/flap deployment and retraction and flight speed. In order to quantitatively determine the available reduction potential, current and preferred (optimal) operations can be modelled. Emissions from climb and descent operations that have an impact on the local airport environment can be identified as CO_2, NO_x, H_2O, PM, CO, unburned hydrocarbons and noise. When applying CDO/CCO rather than a stepped approach and descent or stepped climb operation, reductions in emissions is achieved. However, due to an elongated cruise segment, the amount of CO_2 and non-CO_2 emissions at higher altitudes increases. The precise effect of reduction and displacement of emissions is not obvious and can be obtained through model calculations.

Impact on stakeholders and operations

A variety of stakeholders are involved in the implementation and deployment of CDO/CCO, each fulfilling a different role and experiencing different impacts. With respect to this OI, ANSPs' role is the implementation of structures and airspace/procedure/route design that enable CDO/CCO and to offer guidance to pilots. This, if not combined with enabling technologies, may induce a higher workload for ATCOs [i]. The airlines' role lies in training pilots in best practices and adopting CDO and CCO in their standard operating procedures. For airlines, this will mean a possible reduction of operating costs (lower fuel use) but also additional training and implementation costs. Additionally, CDO/CCO can reduce flight time, because of an absence of low-speed-level segments, and thus decrease crew and maintenance costs [iii]. CCO/CDO requires higher separation minima, which results in reduced available space to handle the air traffic. Consequently, the pressure on ATC increases, which will lead to reduced capacity at high traffic density airports [iv]. This will result in fewer aircraft movements on the airport and a decrease in profits. If the number of flights exceeds maximum capacity, air traffic controllers might require more manoeuvring distance or holding patterns that increase airborne time emissions. In order to mitigate this impact, airports may invest (alongside ANSP) in technologies that enable CDO/CCO without reducing capacity. Residents and nature surrounding airports will generally be positively impacted due to the implementation of more CDO/CCO. Most communities will experience less air pollution and noise. However, due to the concentration of flights, for instance, with a fixed approach, a small percentage of residents may experience an increase in noise and pollution.

2.2.2 Preliminary assessment of the OI

Table 3: KPIs related to Continuous climb/descent operations

KPI	Unit	Value	References
K1 ATR (20/100)	K	TBD	
K2.1 CO_2	kg/cycle	-145/-48kg	[ii]
K2.2 NO_x	kg/cycle	TBD	
K2.3 H2O	Kg/cycle	34-55kg	[v]
K2.4 PM	kg/cycle	TBD	
K3 Fuel flow	Kg fuel/unit time	TBD	
K4 LTO cycle	Cycles per unit time	TBD	
K11 Accident rate ground and TMA	# of accidents per movement	TBD	
K21.1 On time perf (delay)	Delta in unit time	TBD	
K24 Airspace capacity	Landings/hour, takeoffs/hour	TBD	
K33 Travel time	Unit time	-168s	[v] (only CDA)
K38 Airline expense	CASK	TBD	
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	

Table 4: Advantages and disadvantages of Continuous climb/descent operations

Advantages	Disadvantages
Reduced fuel flow (and fuel cost)	Higher concentration of noise load (with fixed routes)
Reduced CO_2 and non- CO_2 emissions	Potentially higher ATM workload
Reduced noise load	Potentially lower airport throughput
Reduced flight time	
Reduced crew and maintenance cost	
Reduced pilot workload	

2.2.3 References

[i] Efthymiou, Marina & Fichert, Frank & Lantzsch, Olaf. *Workload Perception of Air Traffic Control Officers and Pilots During Continuous Descent Operations Approach Procedures. Aviation Psychology and Applied Human Factors*. 2019, vol. 9. pp.2-11. doi:10.1027/2192-0923/a000154.

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2.3 Departure/arrival management extended to en-route airspace

2.3.1 Description and impact of the OI

Arrival Manager (AMAN) and Departure Manager (DMAN) are decision-support tools that are used in the flow management of arrival and departure traffic, respectively. The aim is to sequence air traffic according to the required separation standards and increase the throughput for arrival/departure traffic while ensuring safe and secure airspace use. The integration of AMAN and DMAN improves the performance of the system. Integrated AMAN and DMAN aspires to enhance throughput and predictability in TMAs and at airports by advanced coordination between en-route, approach and tower controllers. Arrival and departure flows are integrated by establishing a standard arrival/departure pattern for specific periods. Departure flow to the runway is governed by pre-departure sequencing, while arrival flow to the runway is handled by arrival metering. Extending the integrated system to en-route airspace improves the efficiency of the management procedure. The Extended Arrival Management (E-AMAN) concept ensures the metering of air traffic into a busy Terminal Movement Area (TMA) from far out in the en-route airspace [i]. This is accomplished by extending the operation horizon of AMAN from the airspace in close proximity to the airport to a horizon further upstream in adjacent en-route airspace. Generally, a SWIM-compliant[1] information-exchange infrastructure is used to implement an E-AMAN solution and deliver E-AMAN output information to controllers upstream.

With the help of E-AMAN, en-route controllers can inform pilots to modify aircraft speed before Top of Descent, so the travel time in the TMA can be reduced. From the airline's perspective, this leads to a reduction of time spent holding stacks and a decrease in fuel consumption and emissions. For the implementation of E-AMAN, there is no requirement for specific avionics equipment beyond what is currently needed for operating in European airspace, and it will not be necessary to update Airline Operations Centre (AOC) systems either. Hence, this strategy will not increase the cost of the airline. However, the ATM systems of the Area Control Center (ACC) would need to be upgraded to accommodate the new features, with a consequent increase of infrastructural costs. The adaptation of the ACC procedures may also be required. The speed control may need to be used more often, thus increasing controller workload in ACC. In this case, the air traffic controller's workload in approach control (APP) will be reduced. Besides, improved cross-border coordination will create new opportunities for the development of operating methods that enable the increased participation of Airspace Users (AUs) through Collaborative Decision Making (CDM) processes. From the standpoint of an airport, extended departure/arrival management will lead to the optimisation of runway throughput, which would increase the number of aircraft on departure/arrival and improve efficiency at the airport. The manufacturer will not be affected by the extended departure/arrival management concept because there is no need to change current aircraft on-board systems. The concept will have a positive impact on society because of the reduction in emissions.

2.3.2 Preliminary assessment of the OI

Table 5: KPIs related to Departure/arrival management extended to en-route airspace

KPI	Unit	Value	References
K1.1 ATR20, K1.2 ATR100	K or °C	TBD	

[1] *The System Wide Information Management (SWIM) concept consists of standards, infrastructure and governance enabling the management of ATM-related information and its exchange between all providers and users of ATM information and services (ICAO Doc.10039).*

KPI	Unit	Value	References
K2.1 CO_2	Kg	15,000 tonnes of CO_2 reduction per year 90 kg of CO_2 reduction per flight	[ii] [i]
K2.2 NO_x	Kg	TBD	
K2.3 H_2O	Kg	TBD	
K2.4 PM	Kg	TBD	
K3 Fuel Flow	Kg	4,700 tonnes of fuel saving per year 30 kg of fuel saving per flight (in the arrival phase)	[ii] [i]
K4 LTO cycle	cycles per unit time	TBD	
K10.1, K10.2 Accident rate - airborne	% change in count of events / frequency of occurrence per flight hour	TBD	
K11.1, K11.2 Accident rate-ground and TMA	% change in count of events / frequency of occurrence per flight hour	TBD	
K21.1 On-time performance	Delay in time per event	Arrival ATFCM delays reduced up to 5% in Paris area	[i]
K23 Movements	Number of aircraft	TBD	
K25.1 Routing efficiency	Added flight distance or time	TBD	
K26.3 Airport capacity	Movements per unit time for runways	TBD	
K27.1 Airport traffic	Movements per unit time	TBD	
K33 Travel time	Time (per event of average over unit time)	TBD	
K38 Airline expense, K39 Airline revenue	CASK, RASK	TBD	
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	

Table 6: Advantages and disadvantages of Departure/arrival management extended to en-route airspace

Advantages	Disadvantages
Reduction of holding times	The ATM systems of the ACC would need to be upgraded to accommodate the new features, thus increasing cost for upgraded systems.
Reduction of fuel burn and emissions	Airspace changes (e.g. introduction of new STARs, a point merge system, etc.) are likely to occur in the TMA airspace, thus increasing cost for updates and raising complexity.
Reduction of delays due to better sequencing	The ACC procedures may need to be adapted. The speed control may need to be used more often, thus increasing controller workload.
Increased efficiency due to the common plan	The transfer of control procedures is expected

Advantages	Disadvantages
between ACC and APP	to be more strict and allow less margin for deviation from the standard procedures, thus increasing complexity.
Reduced workload of the APP controllers	The levels used for transferring aircraft between ACC and APP may need to be reconsidered, thus increasing cost for new design.
The integration of E-AMAN in the ATM systems used by ACC will increase the en-route controllers' situational awareness which in turn would compensate (at least partly) the increased workload.	
Optimised runway throughput	

2.3.3 References

[i] SESAR2020 Project, Airline Team xStream, xStream Demonstration Report, Available: https://cordis.europa.eu/project/id/783116/results. [Accessed: 20-July-2020].

[ii] L3Harris Technologies, Extended Arrival Management, Available: https://www.harris.com/sites/default/files/downloads/solutions/harris_e.aman_data_sheet.pdf. [Accessed: 20-July-2020].

2.4 Free routing in high-complexity environment/flexible waypoints

2.4.1 Description and impact of the OI

The aim of Free Routing is to allow the Airspace Users (AU) to optimise their trajectories by considering their individual business-related needs [i]. In this concept, AUs are able to fly their preferred route between pre-defined navigation points without being limited by following the fixed ATS-routes or published directs, thus gaining in efficiency. The purpose of the Free Routing Area (FRA) concept is to bring various, significant benefits such as using straight flight profiles, less fuel consumption, and operating costs reduction [i]. The environmental footprint can also be reduced by avoiding climate-sensitive areas. Free routing has to be used along the full flight path to take full advantage of this concept. The expected outcome will be more beneficial with Cross Border Free Route Airspace, which allows enhanced optimal planning since the flights will not change their optimal track [iii]. Cross Border Free Route Airspace aims to approve safe and efficient cross-border operations in free routing airspace with minimum structural constraints rather than unrestricted free routing operations.

Air Traffic Control Operator (ATCo) tasks will become more complicated since the trajectories will be more variable and flexible, the crossing points will become random, and the mandatory coordination points on sector boundaries will not be available. In order to overcome those drawbacks, ATCo support systems play a big role in FRA to provide situational awareness, coordination, conflict detection, and aid for decisions/actions regarding conflicts. In addition, both planning and execution phases of the Demand & Capacity Balancing have to be able to facilitate the new, highly complex, and dynamic environment including processes such as Integrated Network Management, extended ATC Planning, and Airspace Management. Besides, Flight Operation Centres (FOC) also have to be developed and integrated with System Wide Information Management (SWIM) Infrastructure, which will allow all AU to plan and follow the most efficient trajectory.

Several stakeholders will be affected by the free routing concept. The concept is expected to observe an increase in controllers' workload by considering the individual trajectory interactions. Advanced decision-support systems for controllers in visualization, conflict detection, resolution options assessment, screen-to-screen electronic coordination support will be required, which leads to additional investment costs for air traffic control services. From the standpoint of Airspace Users (AUs), they will optimise their flight plans with regards to time, flight distance, fuel, and cost by considering both their mission requirements and business needs, through AU preferred routes. FRA will be beneficial for them in terms of fuel efficiency, flight emission reduction, and flight predictability without degrading safety and capacity [ii]. Moreover, en-route safety and capacity can be maintained, even improved. The performance and the capacity of the airspace can be enhanced, and more flights can be managed since the airspace flexibility is predicted, and airspace availability is known, consistently. Thus, operating costs can be reduced, which is an advantage for air traffic service and airline. Additionally, FRA will help to create greener airspace by having a positive impact on greenhouse gas emissions via trajectory optimisation. Hence, the concept will have a positive impact on society. Besides, passengers could be affected positively as a consequence of shorter travelling times.

2.4.2 Preliminary assessment of the OI

Table 7: KPIs related to Free routing in high-complexity environment/flexible waypoints

KPI	Unit	Value	References
K1.1 ATR20, K1.2 ATR100	K or °C	TBD	
K2.1 CO_2	Kg	reduction of 83.69 kg	[i]

KPI	Unit	Value	References
		of CO2 per flight 83 kg of CO_2 per flight	 [iii]
K2.2 NO_x	Kg	TBD	
K2.3 H_2O	Kg	TBD	
K2.4 PM	Kg	TBD	
K3 Fuel Flow	Kg	26.57kg of fuel saving per flight 25 kg of fuel saving per flight	[i] [iii]
K10.1, K10.2 Accident rate - airborne	% change in count of events / frequency of occurrence per flight hour	TBD	
K21.1 On-time performance	Delay in time per event	TBD	
K23 Movements	Number of aircraft	TBD	
K24 Airspace capacity	Movements per unit time	TBD	
K25.1 Routing efficiency	Added flight distance or time	-4.2 NM per flight	[iii]
K33 Travel time	Time (per event of average over unit time)	TBD	
K38 Airline expense, K39 Airline revenue	CASK, RASK	The NPV (Net Present Value) is positive with a gain estimated at 797 M€. 7.5 million Euro per year (estimated direct cost savings)	[i] [iii]
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	
K59.1, K59.3	Passengers' and societal acceptance	TBD	

Table 8: Advantages and disadvantages of Free routing in high-complexity environment/flexible waypoints

Advantages	Disadvantages
Advanced flexible use of airspace	The increased flight planning freedom provided to AUs (Airspace Users) through FRA (free routing airspace) operations, may lead to greater uncertainty in Traffic Forecast accuracy and an impact on Demand Capacity Balancing (DCB) efficiency.
Allow to better accommodate individual AUs' business needs such as low cost, shorter time, shorter distance.	Invest in the training of ATCOs for both basic and advanced solutions, thus increasing training costs.
Reduced fuel consumption and emissions (because of more direct routes and better route planning)	ATCo will consequently need appropriate tools to manage tactical conflict, thus the additional cost for new decision support tools.
High utilization of the airspace	
Shorter routes	

2.4.3 References

[i] PJ06 Trajectory Based Free Routing (ToBeFREE), Final Project Report, Available: https://cordis.europa.eu/project/id/734129/results. [Accessed: 10-July-2020].

[ii] PJ06 Trajectory Based Free Routing (ToBeFREE), Cost Benefit Analysis for V3, Available: https://cordis.europa.eu/project/id/734129/results. [Accessed: 10-July-2020].

[iii] Free Route Airspace Maastricht and Karlsruhe (FRAMaK), Final Project Report, Available: https://www.sesarju.eu/sites/default/files/D12_FRAMaK_Final_Report_00_02_03_withAnnex-red.pdf. [Accessed: 10-July-2020].

2.5 Formation flying

2.5.1 Description and impact of the OI

The aerodynamic formation flight is also known as Aircraft Wake-Surfing for Efficiency (AWSE) promises high fuel savings and can be considered as one of the most capable operational procedures to reduce CO_2 and NO_x emissions of air traffic. This procedure is known for over a century as it can be found in nature, where migratory birds perform aerodynamic formations to extend their range. Inspired by this behaviour AWSE was adapted to man-made aircraft and has been subject to flight testing and simulations for several decades. Up to date flight tests of two-aircraft formations performed by Air Force Research Lab (AFRL) and NASA proved the high potential of this procedure also in practice, using a minimum set of additional systems to establish and conduct the controlled flight in the vortex of a preceding aircraft. However, the extent of the expected benefits and, therefore, the reduction of climate impact depends on the formation route geometry, which is generally defined by the rendezvous and separation points as well as the resulting routing in between these points. Additionally, the necessity to fly together requires multiple flights to converge to a common point of operation in space and time. This implies that frequently at least one of the formation members would not be flying at optimal conditions (e.g. not at the optimal speed or not along the optimal route, etc.). This aspect adds another constraint to the choice of flights for which pairing is beneficial.

As the conduction of AWSE requires the merging of at least two aircraft trajectories airlines, airports and Air Navigation Service Providers (ANSP) need to enable the simultaneous arrival at the rendezvous points by rearrangement of their flight plans, or prioritization of formation members. Aircraft manufacturers and component suppliers need to develop and integrate new automation and sensor systems to enable the automatic conduction of AWSE and authorities need to permit the new procedure and to set up regulations and best practices to safely conduct the necessary manoeuvres. Finally, passengers might be influenced by AWSE due to changed flight plans and a possible slight discomfort during the AWSE conduction.

2.5.2 Preliminary assessment of the OI

Table 9: KPIs related to Formation flying

KPI	Unit	Value	References
K3 Fuel Flow (λ_f)	Relative change of fuel consumption in relation to reference of formation [%]	6% to >7% decrease 5% to >7% decrease	[ii], [iii]
K3 Fuel Flow (m_{Bf})	Absolute change of fuel consumption of formation [kg]	4700 kg to 6700 kg decrease over a distance of ~3000nmi	[iii]
K25.1 Routing Efficiency (σ)	Relative detour in relation to reference of formation member [%]	0% to 4% increase	[iii]
K1.1 ATR20 (ΔATR)	Relative difference of the temperature responses from the AWSE and the reference scenario related to the reference scenario [%]	22% to 24% decrease	[i], [iv]

K10.1, K10.2 Accident rate - airborne	change in count of events and/or frequency of occurrence per flight hour [%]	TBD	
K57 Additional training time	Relative increase in training hours required to perform formation-flying manoeuvres [%]	TBD	
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	
K59.1	Passengers' acceptance	TBD	

Table 10: Advantages and disadvantages of Formation flying

Advantages	Disadvantages
Lower fuel burn	Longer flight times
Reduced climate impact	Longer flight distances
Many opportunities exist today	Possible passenger discomfort
Conventional aircraft can be used	Additional coordination necessary
Additional airspace saturation effects further reduce climate impact	Uncertainties in planning
	Common point of operation needed

2.5.3 References

[i] K. Dahlmann, S. Matthes, H. Yamashita, S. Unterstrasser, V. Grewe and T. Marks, "Assessing the climate impact of formation flights," submitted to 3rd ECATS Conf., Gothenburg, Sweden, 2020.

[ii] T. Marks and M. Swaid, "Optimal Timing and Arrangement for Two-Aircraft Formations on North Atlantic under Consideration of Wind," in *Proc. AIAA SciTech Forum*, Orlando, FL, USA, 2020.

[iii] T. Marks, M. Swaid, B. Lührs and V. Gollnick, "Identification of optimal rendezvous and separation areas for formation flight under consideration of wind," in *Proc. 31st Congr. Int. Counc. Aeronaut. Sci.*, Belo Horizonte, Brasil, 2018.

[iv] T. Marks, K. Dahlmann, V. Grewe, V. Gollnick, F. Linke, S. Matthes, E. Stumpf, S. Unterstrasser, H. Yamashita and C. Zumegen, "Climate Impact Mitigation Potential of Formation Flight," submitted to 3rd ECATS Conf., Gothenburg, Sweden, 2020.

2.6 Flying low and slow

2.6.1 Description and impact of the OI

The concept “Flying low and slow” is based on the idea to systematically reduce the cruise altitude of flights relative to today’s typical flight altitudes, e.g. from 36.000 ft to 28.000 ft. This normally implies a decrease in cruise speed as well. Even if a normal cruise Mach number is selected, the True Airspeed will decrease, as it depends on the ambient temperature, which –below the tropopause- is a function of altitude. This operational measure can be implemented with only minor preparations using existing aircraft. However, additional potential can be gained if aircraft are designed for lower altitudes and lower cruise speeds.

Whether the concept can be considered as an Operational Improvement certainly depends on the stakeholder perspective. Aircrafts flying under off-design conditions 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 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. However, 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 [iv], [v]. 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 CO_2 penalties. In this case, the measure can be considered as an Operational Improvement from a **climate perspective.** 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 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.

More specifically, research has shown that increasing flight altitude leads to an increase in contrail coverage at low latitudes, whereas reducing the contrails coverage in mid-latitudes [v]. Flying at higher altitude leads to a large amount of water vapour emitted in the stratosphere, where water vapour emissions accumulate due to the lack of major loss process hence increasing the atmospheric water vapour concentration and its warming effects [iv].

Frömming et al. (2012) showed that when flying at a lower altitude, the global mean radiative forcing of short-lived species and methane is reduced, whereas that of CO_2 increases, indicating a potential trade-off between CO_2 and non-CO_2 effects [iii]. Furthermore, this study also indicated that for increasing and sustained emissions, non-CO_2 effects dominate the changes in climate effects; hence, a lower flight altitude would be beneficial for climate. However, for future scenarios involving a reduction or termination of emissions, the CO_2 effect is more dominant, hence flying at lower altitude leads to an increase in the aviation’s climate impact. Therefore, scenarios and time horizons for evaluation of future effects of mitigation strategies are critical and should be carefully selected. The study of Koch (2013) assessed the reduction potential of climate impact for the world fleet of a representative long-range aircraft operated on a global route network [ii]. The average temperature response (ATR) and direct operating cost (DOC) were calculated for flights concerning various cruise altitudes and speeds. The analysis found that by reducing the flight altitude and speed, there exists a large potential in reducing the climate impact from aviation at moderate increments on operating costs, e.g., 10% increase in DOC would allow about 27% reduction in climate impact.

2.6.2 Preliminary assessment of the OI

Table 11: KPIs related to Flying low and slow

KPI	Unit	Value	References
K1.2 ATR100 ($\Delta ATR_{100,rel}$)	Relative changes in Average Temperature Response over 100 years (fleet average) [%]	-10.7/-31.2/-41.8/-56.3/61.9 for altitude changes of -3576/-7260/-10928/-19088/-23153ft	[ii] A330-200 fleet (fleet level)
K3 Fuel Flow ($\Delta fuel_{,rel}$)	Relative changes in mission fuel (fleet average) [%]	+5/+12/+18/+34/+40 for altitude changes of -3576/-7260/-10928/-19088/-23153ft	[ii] A330-200 fleet (fleet level)
K10.1, K10.2 Accident rate - airborne	% change in count of events / frequency of occurrence per flight hour	TBD	
K23 Movements	% change in aircraft operating in airspace sectors	TBD	
K25.1 Routing Efficiency ($\Delta time_{,rel}$)	Relative changes in flight time (fleet average) [%]	-3/+3/+10/+18/+34 for altitude changes of -3576/-7260/-10928/-19088/-23153ft	[ii] A330-200 fleet (fleet level)
K38 Airline expense ($\Delta COC_{,rel}$)	Relative changes in Cash Operating Costs (fleet average) [%]	+1/+5/+10/+20/+30.2 for altitude changes of -3576/-7260/-10928/-19088/-23153ft	[ii] A330-200 fleet (fleet level)
K48 Radiative Forcing (ΔRF_{2100})	Changes in Global Annual Mean Net Radiative Forcing [mW/m²]	-41.8/-29.0/-15.8/ +11.1 for altitude changes of -6000/-4000/-2000/+2000ft	[iii] Fa1 scenario (global level)
K49 surface temperature ($\Delta T_{surf,2100}$)	Changes in surface temperature in 2100 [mK]	-22.3/-15.7/-8.9/+6.7 for altitude changes of -6000/-4000/-2000/+2000ft	[iii], Fa1 scenario (global level)
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	
K59.1	Passengers' acceptance	TBD	

Table 12: Advantages and disadvantages of Flying low and slow

Advantages	Disadvantages
Reduced climate impact for comparably low additional costs	Increased flight times
Could be introduced without large preparatory effort (changing regulations, enabling technologies etc.)	Increased fuel consumption
	Increased DOC
	Increased airspace demand on lower flight

	levels
	Lack of incentives

2.6.3 References

[i] K. Dahlmann, A. Koch, F. Linke, B. Lührs, V. Grewe, T. Otten, D. Seider, V. Gollnick and U. Schumann, „Climate-Compatible Air Transport System – Climate Impact Mitigation Potential for Actual and Future Aircraft," *Aerospace*, vol. 3, no. 4, pp. 1–25, Nov. 2016, doi: 10.3390/aerospace3040038.

[ii] A. Koch, "Climate impact mitigation potential given by flight profile and aircraft optimisation," doctoral dissertation, Hamburg University of Technology, 2013.

[iii] C. Frömming, M. Ponater, K. Dahlmann, V. Grewe, D. S. Lee, and R. Sausen, "Aviation-induced radiative forcing and surface temperature change in dependency of the emission altitude," *J. Geophys. Res.*, vol. 117, no. D19104, 2012, doi:10.1029/2012JD018204.

[iv] V. Grewe and A. Stenke, "AirClim: An efficient tool for climate evaluation of aircraft technology," *Atmos. Chem. Phys.*, vol. 8, no. 16, pp. 4621–4639, 2008.

[v] F. Yin, V. Grewe, C. Frömming, and H. Yamashita, "Impact on flight trajectory characteristics when avoiding the formation of persistent contrails for transatlantic flights," *Transp. Res. Part D Transp. Environ.*, vol. 65, pp. 466–484, Dec. 2018.

2.7 Optimal separation minima

2.7.1 Description and impact of the OI

The parameters that are used to determine the separation minima are navigation performance/accuracy, aircraft's exposure to risk/collision probability, and the mitigation measures that are available to reduce risk. The minimum separation also depends on the availability of a radar surveillance service and on the communication type between AUs and ATC. The separation minima currently in use are determined according to information obtained from primary radar data. Because such data have significant inaccuracies, relatively large separation minima between aircraft are adopted to guarantee a buffer and enough space to controllers and pilots to take appropriate actions [ii]. Although flight data collection techniques and radar technologies have strongly improved over the years, the same conservative separation standards have been in use for decades. Because the separation minima are determined according to information obtained from primary radar data, and the primary radar data have inaccuracies, limits are large to provide separation between aircraft. Large buffers give enough space to controllers and pilots to take appropriate actions [ii]. However, it decreases efficiency and leads to a reduction in capacity usage. The idea of reducing the minima would lead to a reduction in flight distance and fuel consumption because of less deviation from the original flight routes and would improve the throughput.

The most important factor determining separation minima is air traffic safety. The mathematical/statistical model of the separation minima can be formulated by considering the correlation between collision risk, separation minima, airspace design, air route network characteristics, flow parameters, intervention capability and communication, navigation and surveillance equipment performance [i]. Since some of those elements include complex parameters to the model, such as human performance, surveillance, communications, and navigation, the separation minima has to be studied properly. There are efforts that are being made in this direction, and, indeed, SESAR 2020 Wave 2 PJ02-WP04 aims to increase the efficiency of runway operations by optimising separation minima in capacity-constrained airports.

Determining the separation minima is a procedure that needs to be done at international (ICAO) level to ensure global harmonisation in air traffic. Thus, changing this concept requires mutual consent internationally [i], which makes it difficult to bring a new concept in that specific area. However, it is possible to reduce separation minima to increase efficiency and obtain economic benefits. The problem is that the possible risks must be predicted with high confidence as the separation minima have a huge effect on the safety in aviation [ii]. The reduced separation minima will bring several benefits such as reduced fuel consumption and emissions, less deviation from original routes, and minimal intervention by Air Traffic Controller (ATCo). The optimal separation minima concept will have a positive impact on airlines and ATC. From the airline's perspective, this concept will lead to less deviation from the planned trajectories. Hence the strategy will cause a reduction in fuel consumption and emissions. An airline can fly more economically because of the reduced fuel consumption, and the reduced emissions will lead to greener airspace. From the standpoint of ATC, the number of interventions will be reduced because of the reduced separation minima. Thus the concept will decrease the controller workload. In this case, airspace capacity would be increased, which is a positive outcome for airspace users (AUs). The manufacturer will not be affected by this concept because there is no need to change current aircraft on-board systems. Society will be positively affected because of reduced emissions.

2.7.2 Preliminary assessment of the OI

Table 13: KPIs related to Optimal separation minima (The research on this OI is limited. Further analysis will be conducted in ClimOp to assess the impact of OI on relevant KPIs)

KPI	Unit	Value	References
K1.1 ATR20, K1.2 ATR100	K or °C	TBD	
K2.1 CO_2	Kg	TBD	
K2.2 NO_x	Kg	TBD	
K2.3 H_2O	Kg	TBD	
K2.4 PM	Kg	TBD	
K3 Fuel Flow	Kg	TBD	
K10.1, K10.2 Accident rate - airborne	% change in count of events / frequency of occurrence per flight hour	TBD	
K11.1, K11.2 Accident rate-ground and TMA	% change in count of events / frequency of occurrence per flight hour	TBD	
K21.1 On-time performance	Delay in time per event	TBD	
K23 Movements	Number of aircraft	TBD	
K24 Airspace capacity	Movements per unit time	TBD	
K25.1 Routing efficiency	Added flight distance or time	TBD	
K26.3 Airport capacity	Movements per unit time for runways	TBD	
K27.1 Airport traffic	Movements per unit time	TBD	
K33 Travel time	Time (per event of average over unit time)	TBD	
K38 Airline expense, K39 Airline revenue	CASK, RASK	TBD	
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	

Table 14: Advantages and disadvantages of Optimal Separation Minima.

Advantages	Disadvantages
Reduced fuel consumption and emissions because of less deviation from planned route	It is hard to implement because a consensus is necessary
Reduced ATC workload	It is difficult to estimate risks with high confidence

2.7.3 References

[i] ICAO, Doc 9689, Manual on Airspace Planning Methodology for the Determination of Separation Minima, 1998.

[ii] P. Brooker, "Air traffic control separation minima: Part 1-the current stasis," J. Navig., vol. 64, no. 3, pp. 449–465, 2011.

2.8 Climate-optimised flight planning

2.8.1 Description and impact of the OI

While most current flight planning is tailored to minimising flight time and fuel consumption (CO_2 emissions), additional effort is needed to further reduce non-CO_2 effects, from NO_x, water vapour, and contrails, which cause about 50% of aviation's climate impact [i]. Climate optimised flight planning takes into account the whole set of CO_2 and non-CO_2 effects and investigates the most promising strategies in reducing the aviation's climate impact. In addition to the quantity of the emission, the time, location, background concentration, and local meteorology strongly influence the impact of non-CO_2 effects on the climate.

Regions where non-CO_2 effects are large are termed climate-sensitive areas, which can be avoided through flight trajectory optimisation as studied by Grewe et al. [ii]. The study applied this optimisation strategy for typical summer and winter patterns as characterised by Irvine et al. [iii] in the Trans-Atlantic airspace for a large number of eastbound and westbound flights. It was found that for small changes in routing, climate impact reduction of 10% was possible with a 1% increase in operating cost. With certain suggested market-based measures, the same climate reduction can be maintained with a 5% decrease in operating costs. The study also found that there was a larger variability for west-bound flights in winter; and in the summer, the climate reductions were shown to be greater for both westbound and eastbound flights. The reader is referred to figure 2 of Grewe et al. [ii] for details.

Another study [iv] shows the climate impact reduction potential of contrails, ozone and aviation NO_x, which are in terms of Absolute Global Warming Potential for a time horizon of 100 years (AGWP100). Results show that while contrails mostly cause warming, some contrails during the day cause cooling. It reports the possibility of obtaining a 25% reduction of the climate impact with economic costs increasing by less than 0.5% for small routing changes.

In [v], a one-day case study with a weather situation containing regions with high contrail impacts for European air traffic estimated an overall climate impact reduction of about 50% with 0.75% additional fuel burn.

Table 35 shows the KPIs in relation to these studies but also those that will be addressed specifically in ClimOp. While these studies show promising results for climate optimised planning, there are other challenges to be addressed within the framework of ClimOp. Further research will help gain consensus on finding a balance between the cooling effect generated by (some) contrail formation and the warming effect caused by the additional CO_2 that is emitted due to the optimisation. Most of the studies evaluate the avoidance of contrail formation by flying at an off-optimal altitude, whereas in the specific case of cooling (daytime) contrails, one could think of deviating from the optimal altitude to deliberately fly into a contrail-formation area. The other challenge is to evaluate the implications caused by optimised routings on ATM. This can also be checked through relevant KPIs.

2.8.2 Preliminary assessment of the OI

Table 15: KPIs related to Climate-optimised flight planning

KPI	Unit	Value	References
K1.1 ATR20	Relative temperature change per unit mass of emission [%]	10% decrease 50% decrease	[ii], [v]
K1.2 ATR100	Relative temperature change per unit mass of emission [%]	TBD	
K48 Radiative	Relative change in	25% decrease	[iv]

KPI	Unit	Value	References
Forcing (AGWP100)	Integrated RF [%]		
K 38 Airline expense	Relative change in cost [%]	<0.5% increase 1% increase 5% decrease (with market-based measures)	[iv], [ii]
K3 Fuel flow	Relative change in fuel per unit time [%]	0.75% increase	[v]

Table 16: Advantages and disadvantages of Climate-optimised flight planning

Advantages	Disadvantages
Reduced climate impact of non-CO_2 effects, [ii],[iv]	Increase in flight time and cost, [ii],[iv]
Large reduction of climate impact possible for small increases in cost [ii],[iv]	More confined airspace for lateral re-routing [ii]

2.8.3 References

[i] D. S. Lee et al., "Transport impacts on atmosphere and climate: Aviation," *Atmos. Environ.*, vol. 44, no. 37, pp. 4678-4734, 2010.

[ii] V. Grewe, S. Matthes, C. Frömming, S. Brinkop, P. Jöckel, K. Gierens, T. Champougny, J. Fuglestvedt, A. Haslerud, E. Irvine and K. Shine, "Feasibility of climate-optimised air traffic routing for trans-Atlantic flights," *Environ. Res. Lett.,* vol. 12, 2017.

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[iv] V. Grewe, T. Champougny, S. Matthes, C. Frömming, S. Brinkop, O. Søvde, E. Irvine, L. Halscheidt, "Reduction of the air traffic's contribution to climate change: A REACT4C case study," *Atmos. Environ.*, vol. 94, pp. 616–625, Sep. 2014.

[v] B. Lührs, F. Linke, S. Matthes, V. Grewe, F. Yin, K. Shine, "Climate impact mitigation potential of European air traffic," submitted to 3rd ECATS Conf., Gothenburg, Sweden, 2020.

2.9 Wind/weather-optimal dynamical flight planning

2.9.1 Description and impact of the OI

The concept of wind/weather-optimal dynamical flight planning aims to minimise the flight operating costs by selecting the most appropriate and efficient route, altitude, speed, and the amount of fuel needed on board. In addition, updated weather forecasts are used to continuously revise the flight route, altitude, and speed since the flight operations have a dynamic structure. To achieve the expected efficiency, forecasting the weather accurately is a key factor. With accurate weather forecasts, in particular of head-winds, tail-winds, and air temperature along the entire flight route, the amount of fuel needed on-board can be predicted very precisely. For fuel-related calculations, many parameters have to be considered, such as weather forecasts, routes and flight levels, physical constraints, and fuel consumption rate. The air temperature has an impact on aircraft engine efficiency. Also, head or tail winds affect the distance to be flown, hereby have an impact on fuel consumption. Route planning process also plays an important role in dynamical flight planning [i], [ii]. The primary purpose of route planning is to provide cost-efficiency in-flight operations by defining optimal flight procedures. Minimising fuel consumption is very important, especially for commercial flights, in terms of economic and environmental issues. Wind/weather-optimal dynamical flight concept will be used to find the optimal route by considering the weather predictions, which have a positive impact on climate changes [i], [iii].

ATCs and Airspace Users will be the most affected stakeholders by the dynamical flight planning system. From the standpoint of ATC, this concept might bring peaks of demand for optimum routes and preferred altitudes. Potentially, demand might exceed capacity in busy air sectors, e.g. in areas with high jet stream, which many flights would like to benefit from. This problem can worsen in busy periods, such as when aircraft want priority to land to an airport or during departure. ATCo may refuse permission for some of the flight plans that are considered as optimal flight routes or delay the allocated take-off slots due to overloading. For this reason, sometimes sub-optimal flight plans, which may include inefficient low altitude, longer but less congested routes, etc., could be filed to avoid overloading and give ATCos flexibility to provide efficient service. Once airborne, the pilot's job is to fly as efficiently as possible, so the pilot might request and negotiate with the controller the allocation of the flight to its optimal routes by asking higher flight level or direct routing. This situation could increase the workload of ATCos. From the standpoint of the airport, the concept could lead to an increase in runway throughput because of wind-optimal arrival/departure flight plans that decrease the deviation from the planned trajectories. For airlines and pilots, a wind/weather-optimal dynamical flight concept based on accurate weather forecast is of great advantage, as it allows flying optimum routes at optimal operating costs and flight time and maximum flexibility in case of changing weather forecast.

2.9.2 Preliminary assessment of the OI

Table 17: KPIs related to Wind/weather-optimal dynamical flight planning

KPI	Unit	Value	References
K1.1 ATR20, K1.2 ATR100	K or °C	TBD	
K2.1 CO_2	Kg	TBD	
K2.2 NO_x	Kg	TBD	
K2.3 H_2O	Kg	TBD	
K2.4 PM	Kg	TBD	
K3 Fuel Flow	Kg	fuel savings between 1.0% – 10.3% saving 1105 kg of fuel for	[iii]

KPI	Unit	Value	References
		JFK-FCO flight saving 2537 kg of fuel for FCO-JFK flight	[iv]
K10.1, K10.2 Accident rate - airborne	% change in count of events / frequency of occurrence per flight hour	TBD	
K21.1 On-time performance	Delay in time per event	TBD	
K23 Movements	Number of aircraft	TBD	
K25.1 Routing efficiency	Added flight distance or time	TBD	
K33 Travel time	Time (per event of average over unit time)	TBD	
K38 Airline expense, K39 Airline revenue	CASK, RASK	TBD	
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	

Table 18: Advantages and disadvantages of Wind/weather-optimal dynamical flight planning

Advantages	Disadvantages
Improved flight planning	Oversubscription of optimum routes and altitudes in busy airspaces
Substantial savings in fuel, miles and time	May lead to increase the workload of ATCos
Emission reduction	

2.9.3 References

[i] B. Girardet, L. Lapasset, D. Delahaye, and C. Rabut, "Wind-optimal path planning: Application to aircraft trajectories," *13th International Conference on Control Automation Robotics and Vision* (ICARCV), pp. 1403–1408, 2014

[ii] O. Rodionova, and S. Banavar, "Efficient Planning of Wind-Optimal Routes in North Atlantic Oceanic Airspace," 2017.

[iii] C. Charlotte, A. Marcos, and O. Turnbull, "Wind optimal flight trajectories to minimise fuel consumption within a 3 dimensional flight network," *11th International Conference on Control (UKACC)*, 2016.

[iv] A. Franco, D. Rivas, and A. Valenzuela, "Optimal aircraft path planning considering wind uncertainty," *Proceedings of the 7th European Conference for Aeronautics and Space Sciences (EUCASS)*, 2017.

2.10 Climate-restricted airspaces

2.10.1 Description and impact of the OI

Non-CO_2 effects of aviation can be effectively mitigated by re-routing flights around highly climate-sensitive areas (see, i.a., the concepts of climate-optimised flight planning, climate optimised North-Atlantic Track System and flying low and slow, respectively in Sections 2.8, 3.4, and 2.6). Even though a climate-optimised re-routing leads to marginally longer flight times, increased fuel consumption and higher operating costs, it is more climate-friendly with a reduction of up to 60% compared to a cost-optimised routing. If, however, mitigation efforts are associated with a direct increase in costs, the question arises to which extent these costs can be carried by airlines and potentially passed through to passengers as a contribution to environmental protection. To enforce climate-optimised flying, the regulatory concept of climate-restricted airspaces (CRA concept) proposes temporary no-fly zones in highly climate-sensitive zones in analogy to military exclusion zones.

In the concept of Climate-Restricted Airspaces, highly climate-sensitive airspace areas are restricted for a period of time (hour, day, etc.), if its climate sensitivity with respect to aircraft emissions[2] exceeds a specific threshold value c_{thr}; otherwise, they are cleared for air traffic [i], [ii]:

$$\mathrm{CRA}(\boldsymbol{x}, t) = \begin{cases} 1, & \text{if } \mathrm{CCF_{tot}}(\boldsymbol{x}, t) \geq c_{thr} \\ 0, & \text{if } \mathrm{CCF_{tot}}(\boldsymbol{x}, t) < c_{thr} \end{cases}$$

In order to ensure easy planning and verifiability of the CRA concept, the central tasks of flight planning, as well as monitoring, reporting and verification (MRV) are designed to be linked to the existing ATC system in such a way that they can be largely taken over directly by the established services:

(a) For climate mitigation, it is neither necessary to monitor CO_2, H_2O and NO_x emissions nor to integrate complex non-CO_2 effects into airline's flight planning procedures. Instead, aircraft operators can continue to operate in a purely cost-optimised manner.
(b) Location and size of (hourly or daily updated) climate-restricted airspace can be defined centrally and rule-based by air traffic control, if the threshold value (c_{thr}) is determined and agreed upon by policymakers based on scientific evidence.
(c) Air traffic control services can check compliance of the CRA concept at any time based on available flight data. Charges are only required in the event of misconduct (unauthorised flight through the restricted area).

The feasibility and effectiveness of the CRA concept have been demonstrated with trajectory simulations on a selected route network in the North Atlantic flight corridor relative to the potential of eco-efficient trajectories [i], [ii]. These studies identified a climate impact mitigation potential of the CRA-concept in the same order of magnitude as climate-optimal flying. For a North Atlantic route network, on average more than 90% of the climate impact reduction potential of climate-optimised trajectories (theoretical maximum) could be achieved by introducing climate-restricted areas. For instance, CRA avoiding trajectories can mitigate the climate impact of a single North Atlantic flight by 10% for a cost increase of less than 1%. The idea of avoiding only the most climate-sensitive regions is therefore, an extremely effective mitigation approach. However, particularly small climate gradients trigger large zones of restrictions, which might reduce the airspace capacity significantly and severely impact the feasibility of the CRA concept in practice.

[2] The climate sensitivity of an area is expressed by total climate change functions ($\mathrm{CCF_{tot}}$) characterizing the environmental impact of non-CO_2 aircraft's emissions at a certain location and time.

The effectiveness of this concept critically depends on the accuracy of locating climate-sensitive areas. Especially for contrail-formation areas, this requires the availability of high-resolution and high-precision meteorological data and instrumentation. It should be kept in mind that only once this is ensured and implemented in all relevant airspaces, the CRA concept is viable.

2.10.2 Preliminary assessment of the OI

Table 19: KPIs related to Climate-restricted airspaces

KPI	Unit	Value	References
K1.1 ATR100 ($\Delta ATR_{100,rel}$)	Relative changes in Average Temperature Response over 100 years [%]	-8.7 / -12.0 / -19.5 / -21.9 / -27.5 / -30.0 / -34.6 / -36.0	[i], [ii]
K38 Airline expense ($\Delta COC_{,rel}$)	Relative changes in Cash Operating Costs [%]	+0.5 / +1.0 / +2.0 / +2.5 / +4.5 / +5.3 / +6.5 / +7.6	[i], [ii]
K3 Fuel Flow ($\Delta fuel_{,rel}$)	Relative changes in fuel burn [%]	+0.9 / +1.6 / + 3.2 / 4.0 / +7.5 / +8.9 / 11.0 / +13.0	[i], [ii]
K25.1 Routing Efficiency ($\Delta time_{,rel}$)	Relative changes in flight time [%]	+0.1 / +0.4 / +1.0 / + 1.4 / +2.2 / +2.6 / +3.1 / +3.4	[i], [ii]
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	
K59.1, K59.3	Passengers' and societal acceptance	TBD	

Table 20: Advantages and disadvantages of Climate-restricted airspaces

Advantages	Disadvantages
CRA concepts create a need for aircraft operator for climate mitigation	Slightly increased flight times and fuel consumption
Reduced climate impact for comparably low additional costs	Increased Cash Operating Costs (COC)
Simple feasibility of required MRV activities	Adverse effect on ATC capacity
	Critical dependence on high-quality meteorological data

2.10.3 References

[i] M. Niklass, B. Lührs, K. Dahlmann, C. Frömming, V. Grewe and V. Gollnick, "Cost-Benefit Assessment of Climate-Restricted Airspaces as an Interim Climate Mitigation Option," *J. Air Transp.*, vol. 25, no. 2, pp. 27–38, 2017, doi:10.2514/1.D0045.

[ii] M. Niklass, B. Lührs, V. Grewe, K. Dahlmann, T. Luchkova, F. Linke and V. Gollnick, "Potential to reduce the climate impact of aviation by climate restricted airspaces," *Transp. Policy*, vol. 83, pp. 102–10, 2016, doi:10.1016/j.tranpol.2016.12.010.

2.11 Climate-charged airspaces

2.11.1 Description and impact of the OI

Non-CO_2 effects of aviation can be effectively mitigated by re-routing flights around highly climate-sensitive areas (see, i.a., the concepts of climate-optimised flight planning, climate optimised North-Atlantic Track System and flying low and slow, respectively in Sections 2.8, 3.4, and 2.6). As stated before, a climate-optimised re-routing may lead to marginally longer flight times, increased fuel consumption and higher operating costs, but it is more climate-friendly with a reduction of up to 60% compared to a cost-optimised routing. To disincentivise non-climate-optimised flying, the price-based concept of climate-charged airspaces (CCA concept) imposes climate charges on airlines when operating in highly climate-sensitive airspace areas. In this concept, an airspace area *j* is levied with an environmental unit charge $\mathrm{U_{cj}}$ per kilometre flown $(\mathrm{d_j})$, if its climate responsibility with respect to aircraft emissions exceeds a specific threshold value c_{thr}:

$$\mathrm{CCA}(\boldsymbol{x},t)=\begin{cases}U_{cj}, & \text{if } \mathrm{CCF_{tot}}(\boldsymbol{x},t)\geq c_{thr}\\ 0, & \text{if } \mathrm{CCF_{tot}}(\boldsymbol{x},t)< c_{thr}\end{cases}$$

By implementing the **polluter-pays principle** and the **precautionary principle** of environmental economics in the field of aviation, the concept integrates the socio-economic costs of climate change into the accounting and decision-making process of aircraft operators. It can therefore be theoretically expected that all affected flights will be diverted at the lowest possible cost around highly climate-sensitive regions, which in turn will cut the climate impact of the flight. This would resolve the existing trade-off between economic viability and environmental compatibility: Climate impact mitigation of non-CO_2 effects will coincide with cutting costs, and eco-efficient flying will become economically attractive. However, this would be the case only in an ideal world; in reality, ATC constraints will allow neither ATCOs nor pilots to always fly the most climate-friendly trajectory, especially if climate-sensitive areas are to be avoided, i.e. congestion will increase in the other areas. The trend for ATCOs to avoid operational procedures, increasing their workload is also to be taken into account.

The resulting climate charge C_{cj} for a flight through a climate charged area j is addressed in analogy to en-route and terminal charges:

$$C_{cj}=U_{cj}\cdot\left(\frac{\mathrm{MTOW}}{k_1}\right)^{k_2}\cdot I_{AC}\cdot d_j$$

where MTOW is defined as the maximum take-off weight of an aircraft and $\mathrm{I_{AC}} \in [0,1]$ as incentive factor for climate-friendly technologies:

$$I_{AC}=\begin{cases}1 & \text{for current aircraft technology standards}\\ \vdots & \text{for more efficient aircraft technology standards}\\ 0 & \text{for zeroemission aircraft}\end{cases}$$

By combining the climate charge $\mathrm{C_{cj}}$ with an incentive factor for more efficient aircraft technologies standards, the profitability of sustainable capital investments – especially of more electric aircraft systems – is increasing. If, for instance, hybrid-electric aircraft switch on the electric-drive while flying through climate-charged areas, no climate charges have to be paid.

In line with the CRA concept (section 2.10), central flight planning and MRV tasks are designed to be easily integrated into established procedures:

(1) Aircraft operators can continue to operate in a purely cost-optimised manner without monitoring CO_2, H_2O, and NO_x emissions or integrating complex non-CO_2 effects into airlines' flight planning procedures.

(2) CCAs can be designed rule-based on an hourly or daily basis by air traffic control, if level of climate charged (U_{cj}) and threshold value (c_{thr}) is determined and agreed upon by policymakers on the basis of scientific evidence.
(3) Climate charges are calculated in analogy to en-route and terminal charges
(4) Air traffic control services can check compliance of the CRA concept at any time based on available flight data.

Niklaß et al. (2018, 2020) [i], [ii] simulated the feasibility and effectiveness of the CCA concept on a selected route network in the North Atlantic air corridor relative to the potential of eco-efficient trajectories (benchmark). They demonstrated that the additional costs of internalization (climate-charges), can largely be avoided by re-routing the flights (partly) around CCAs. Thus, it is possible to achieve, on average more than 90% of the climate mitigation potential of climate-optimised trajectories (theoretical maximum). The idea of avoiding only the most climate-sensitive regions is therefore, an extremely effective mitigation approach. Key parameters of the CCA concept are threshold value (c_{thr}), defining the size and location of CCAs, and the climate unit charge $(\mathrm{U_{cj}})$. The higher $\mathrm{U_{cj}}$, the greater is the financial incentive for re-routing, while keeping the mitigation potential almost unchanged. The opposite is true for the threshold: Size of climate-charged areas increases with decreasing threshold, which in turn raises the mitigation potential of the CCA concept for a constant incentive level. According to Niklaß et al. (2020) [i], [ii], it is also possible to identify an optimal set of these parameters for an entire route network to create a monetary incentive on each route for a targeted mitigation potential, e.g. to ensure a climate impact reduction of at least - 5% on each North Atlantic flight.

However, particularly small climate gradients trigger large zones of restrictions, which might reduce the airspace capacity significantly.

The effectiveness of the CCA concept, like that of the CRA concept, critically depends on the accuracy of locating climate-sensitive areas. Especially for contrail-formation areas, this requires availability of high-resolution and high-precision meteorological data and instrumentation. It should be kept in mind that only once this is ensured and implemented in all relevant airspaces, the CCA concept is viable.

2.11.2 Preliminary assessment of the OI

Table 21: KPIs related to Climate-charged airspace

KPI	Unit	Value	References
K1.1 ATR100 ($\Delta ATR_{100,rel}$)	Relative changes in Average Temperature Response over 100 years [%]	Same as for eco-efficient trajectories	[i], [ii]
K38 Airline expense ($\Delta COC_{100,rel}$)	Relative changes in Cash Operating Costs [%]	Highly dependent of key parameters. An optimal set of these parameters can be found for a route network to create a monetary incentive for a targeted mitigation potential on each route	[i], [ii]
K3 Fuel Flow ($\Delta fuel_{,rel}$)	Relative changes in fuel burn [%]	Same as for eco-efficient trajectories	[i], [ii]
K25.1 Routing Efficiency ($\Delta time_{,rel}$)	Relative changes in flight time [%]	Same as for eco-efficient trajectories	[i], [ii]

K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	
K59.1, K59.3	Passengers' and societal acceptance	TBD	

Table 22: Advantages and disadvantages of Climate-charged airspace

Advantages	Disadvantages
Implementation of the polluter-pays principle and the precautionary principle of environmental economics	Slightly increased flight times and fuel consumption
CCA concepts creates a financial incentive for climate mitigation	Increased Cash Operating Costs (COC)
Simple feasibility of required MRV activities	Adverse effect on ATC capacity
	Critical dependence on high-quality meteorological data

2.11.3 References

[i] M. Niklass, B. Lührs, V. Grewe and V. Gollnick, "Implementation of eco-efficient procedures to mitigate the climate impact of non-CO_2 effects," in *Proc. 31st Congr. Int. Counc. Aeronaut. Sci.*, Belo Horizonte, Brasil, 2018.

[ii] M. Niklass, V. Grewe and V. Gollnick, "A systems analytical approach for internalizing the climate impact of aviation," *Aerospace* (in publication), 2020.

3. Climate-optimised trajectory

This chapter is focused on the preliminary assessment of various OIs related to the climate-optimised trajectory. There are in total five OIs being considered, including routing optimised for contrail (night) avoidance, climate optimised intermediate stop, trade flight frequency for aircraft size, climate-optimised North-Atlantic organised track system, and strategic planning. These OIs influence the aviation sector in different ways. For instance, contrail avoidance would reduce the contrail induced climate impact at the expense of flight time and cost. OIs of different network configurations and trade flight frequency for aircraft sizes are affecting the network planning, flight frequency and aircraft sizes. Details on the characteristics of each OI and their impacts on different aviation KPIs are presented in this section.

3.1 Routing optimised for contrail (night) avoidance

3.1.1 Description and impact of the OI

Contrails contribute to a large part (> 50%) of overall aviation induced global warming [i]. The net Radiative Forcing (RF) for nighttime contrails can only be positive (warming) and hence, avoiding their formation is of significant importance to reduce aviation's climate impact. Earlier studies have shown the evidence of avoiding (night) contrails via flight detouring. As will be discussed, some studies also indicate that a small fraction of flights are responsible for a significant fraction of contrail effects, and avoiding these can be very beneficial. For the preliminary assessment of contrail avoidance, results pertaining to the impact are discussed from multiple research projects. This helps in understanding the potential benefits of this OI.

Yin et al. (2018) studied the impacts of lateral and vertical changes on flight trajectories when avoiding the formation of persistent contrails for Trans-Atlantic flights [ii]. The study involved finding a reasonable trade-off between flight time and potential contrail coverage. The mitigation strategy resulted in up to 40% reduction in contrail coverage for a flight time increase of less than 2%. The study also found seasonal variations for the change in contrail coverage. While it did not directly compute climate impact, it showed a significant decrease in contrail coverage, which implies a reduction in climate impact.

Schumann et al. (2011) investigated flights on 6 June 2006 and calculated integrated radiation changes from contrails and CO_2. They found that by vertical shifts of individual flights, the radiative forcing can be reduced by 97% at an increase of costs of 0.2% [vii].

Sridhar et al. (2012) developed an algorithm to calculate optimal trajectories to avoid regions facilitating persistent contrail formation while taking into account wind field effects [iii]. Regions where persistent contrail formation occurs are modelled as penalty regions where the time spent by an aircraft should be minimised. The study covered the U.S. airspace and found that by varying the flight altitude, a 2% increase in total fuel consumption can reduce the total travel times through the penalty regions by six times.

The REACT4C project [iv], involved the impact of re-routing Trans-Atlantic flights to avoid climate-sensitive regions on a specific winter day. This study took into account the effects of contrails, NO_x (Ozone and Methane), and CO_2. With respect to contrails, a linear reduction potential was documented when achieving 25%, 50%, 75% and 100% of the maximum climate impact reduction in terms of Absolute Global Warming Potential (P-AGWP) over 100 years. The study additionally shows that day contrails can sometime cause cooling, but nighttime contrails always cause warming.

A new study [v] calculated contrail inventories for the U.S. airspace over one year and found that only a small percentage of daily flights (average of 15%) generated contrails, most of which were generated in the South-Eastern U.S. and the Pacific Coast. This coverage was also found to be more profound between June and September, indicating seasonal effects. The study exploited these findings to mitigate the climate effect of contrails by imposing cruise flight altitude changes of +2000 ft. and +4000 ft. The analysis indicated a reduction in (daily) contrail-forming flights by 14.8%, which causes a decrease in net daily RF by 92% with an average reduction in fuel-burn of <1% (due to lower drag at higher altitudes).

A similar study [vi] for the Japanese airspace found that only 2.2% of flights contribute to 80% of the contrail RF in this region. The findings show that a small-scale strategy of selectively diverting 1.7% of the fleet reduces the contrail RF by up to 59.3% with only a 0.014% increase in total fuel consumption and CO_2 emissions.

Below the findings from the aforementioned studies are summarised. Note that while ATR20 and ATR100 are the chosen climate KPIs for ClimOp, other KPIs that have been discussed here are also included.

3.1.2 Preliminary assessment of the OI

Table 23: KPIs related to Routing optimised for contrail (night) avoidance

KPI	Unit	Value	References
K1.1 ATR20	Relative temperature change per unit kilometre of flight coverage [%]	TBD	
K1.2 ATR100	Relative temperature change per unit kilometre of flight coverage [%]	TBD	
K48 Radiative Forcing	Relative change [%]	97% decrease 92% decrease 59% decrease	[vii], [v], [vi]
K48 Radiative Forcing (AGWP100)	Relative change in Integrated RF [%]	25% decrease	[iv]
K50 Contrail coverage	Relative change in distance [%]	40% decrease	[ii]
K3 Fuel flow	Relative change in Fuel per unit time [%]	2% increase 0.014% increase <1% decrease	[iii], [vi], [v]
K33 Travel time	Relative change in duration of travel from point of departure till arrival [%]	<2% increase	[ii]
K38 Airline expense	Relative change in cost [%]	0.2% increase	[vii]
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	
K59.1	Passengers' acceptance	TBD	

Table 24: Advantages and disadvantages of Routing optimised for contrail (night) avoidance

Advantages	Disadvantages
Contrail RF decreases [v],[vi],[vii]	Increase in flight time [ii] and cost [iv],[vii]
Contrail coverage decreases, [ii]	Climate impact potential differs largely due to uncertainties in the numerical model, satellite data, seasonal cycles and general coverage, [vi].
Time spent in contrail regions decreases, [iii]	Increase in fuel burn (CO_2 emissions) [iii],[vi].

3.1.3 References

[i] D. S. Lee et al., "Transport impacts on atmosphere and climate: Aviation," *Atmos. Environ.*, vol. 44, no. 37, pp. 4678-4734, 2010.

[ii] F. Yin, V. Grewe, C. Frömming, and H. Yamashita, "Impact on flight trajectory characteristics when avoiding the formation of persistent contrails for transatlantic flights," *Transp. Res. Part D Transp. Environ.*, vol. 65, pp. 466–484, 2018.

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[iv] V. Grewe, T. Champougny, S. Matthes, C. Frömming, S. Brinkop, O. Søvde, E. Irvine and L. Halscheidt, “Reduction of the air traffic's contribution to climate change: A REACT4C case study,” *Atmos. Environ.*, vol. 94, pp. 616–625, Sep. 2014.

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[vii] U. Schumann, K. Graf and H. Mannstein, “Potential to reduce the climate impact of aviation by flight level changes,” in *Proc. 3rd AIAA Atmos. Space Environ. Conf.*, 2011.

3.2 Climate-optimised intermediate stop-over

3.2.1 Description and impact of the OI

It can be shown with aircraft design mathematical and empirical relationships that the fuel efficiency for transporting a given payload decreases with increasing design range under the same assumptions and with the same technology level. The reason for this is that aeroplanes with a longer range require larger tank capacities, which translate into an increased structural weight (enlarged wings, reinforced wing root). For each additional kilogram in the operational empty weight (OEW), extra fuel is required for the same range, which must be accommodated by the tank volume. These so-called snowball effects lead to a disproportionate reduction in efficiency with increasing range.

The use of aircraft with a shorter range and refuelling, e.g., during stop-overs on long routes, may therefore save considerable fuel. This can also result in a reduction in the pollutants arising in flight and a decrease in direct operating costs. However, fuel savings can also be achieved with existing long-haul aircraft if a stop-over is made to refuel. The theoretically achievable fuel savings increase with increasing mission length, so Intermediate Stop Operations (ISO) can significantly improve fuel efficiency in long-range missions [i].

The possible savings from ISO with an existing aircraft for one stop-over have been investigated by several authors and are in the order of 5-15% depending on the aircraft type used [ii]-[vi]. Poll emphasizes that the gain from one additional stop-over is small (approx. 1.8% with an existing aircraft) [xv]. Therefore, due to further operational aspects, an additional economic benefit of ISO operation per flight with only one stop-over is minor. Linke et al. conducted an extensive system-wide study to determine the implications of ISO with existing aircraft on gaseous emissions and climate. They developed a realistic air traffic simulation taking into account operational constraints and ambient conditions, such as wind, the calculation of engine emissions, and a climate response model. For the worldwide long-range aircraft fleet in 2010, the influence on global emissions distributions and the impact on climate change were determined by taking into account CO_2 and non- CO_2 effects. These effects are arising from contrail-cirrus, water vapour, and nitrogen oxide emissions. In an agreement with earlier findings, it’s suggested that due to shorter flight distances, the amount of fuel burnt over the mission can be reduced by roughly 5% on average globally. Note that on individual very long routes, the savings could be up to 16%. Due to the nitrogen oxide and water vapour emissions released at higher cruise altitudes and over-compensate reduced warming effects from CO_2 and contrail-cirrus, an increased warming effect was found.

Many authors expect a climate-impact reduction for ISO even with existing aircraft, avoiding the higher flight altitude in the first flight segment, and reducing the fuel savings. As discussed in the previous paragraph, pursuing optimisation only with a fuel consumption objective could imply that a global optimum for climate impacts is not reached. The most likely climate impact benefits could be achieved if lower fuel savings were acceptable. This suggestion, namely the adoption of “Climate-optimised Intermediate Stop Operations,” has to be analysed in more detail.

To this end, the application of ISO in civil aviation is pursuing a twofold approach. Redesigning and optimising aircraft for shorter ranges and proposing new operation strategies for airlines to use their fleet more efficiently. In this project, we are focusing on generating different scenarios on how to use ISO as an operational improvement approach for an airline’s existing fleet. ISO is aiming to improve civil aviation operations in terms of flight fuel consumption and emissions. There is a trade-off between the reduction in fuel consumption and emissions, which can be analysed in different scenarios. Developing a general scenario that any airline follows to reach an optimum operation plan seems impossible. To propose an operation scenario, we need a tailored operation scenario, including all active constraints that airline facing in its working atmosphere. On the other hand, taking into account stakeholders that involved this ISO will help in facilitating the procedure of design and implementing of the scenarios [vii]–[xii].

Implementation of a scenario by an airline may cause many internal and external effects. Adding a stop to a candidate long-haul flight increases the travel time for passengers, the need for airport capacity (both on runways and at gates and terminals) and workload for ATCOs and airports. These side effects should be included in a systematic view for both the design and implementation phase to provide a holistic view of the result on the operational improvement scenario.

3.2.2 Preliminary assessment of the OI

Table 25: KPIs related to climate optimised intermediate stop-over

KPI	Unit	Value	References
K38 Airlines expense	Relative Reduction [%]	35%	[vii]
K47 Fuel cost	Relative Reduction [%]	5-10%/ 10% / up to 52% / 5-51%	[vii]-[xv]
K10.1, 10.2, 11.1, K11.2 accident rate (ground, TMA, airborne)	% change in count of events / frequency of occurrence per flight hour	TBD	
K27.1, K27.2, K27.3 Airport traffic	Relative Variation [%]	TBD	
K21.1, K21.2 on-time performance	Total delay and/or relative variation of delay time [%]	TBD	
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	
K59.1, K59.2	Acceptance among passengers and local communities near airports	TBD	

Table 26: Advantages and disadvantages of climate optimised intermediate stop-over

Advantages	Disadvantages
Reducing the flight emissions	Affects airline market share
Reducing fuel consumption	Increased airline network complexity
Increased airline network flexibility	Increased airline and ATC workforce
Increased airline fleet utilization rate	May cause disruption
Potentially more destination choices for passengers due to added stops	Increased noise and local emissions in airport area
Increased customer base due to new stops	Increased total travel time
	Increased maintenance related to flight cycles
	Increased need for airport capacity

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3.3 Trade flight frequency for aircraft size

3.3.1 Description and impact of the OI

The range and size of current aircraft are mostly positively correlated. Smaller aircraft types with lower passenger capacity typically operate on short-haul routes, while larger aircraft types operate long-haul routes. Looking at global flights, short-haul flights (<1500km) make up ~75% of all flights [i]. When considering these two facts, it might be interesting for aircraft manufacturers to design aircraft with higher passenger capacities that are optimised for short-haul flights and for airlines to adopt flight schedules to trade flight frequency for larger aircraft. Using larger aircraft optimised for short-haul routes may potentially reduce global climate impact and operating cost. Lower flight frequencies might help reducing delays, the strain on the airport and ATC system and local noise and emissions.

Of course, airlines are not bound to wait on aircraft manufacturers developing optimized aircraft to apply larger aircraft on short-haul (or medium-haul) routes. If, for example, on a specific route demand is sufficiently high, it can schedule a larger type of aircraft, effectively reducing the number of required LTOs. This method, with some of the afore-mentioned positive impacts (reduced strain on airports and ATC, local noise, delays, etc.) can be adopted, but not without possible negative effects. Airlines that operate more frequently on highly competitive routes do so to gain an advantageous market position over airlines that operate less frequently [ii] by attracting passengers with specific time preferences. Also, operating costs and environmental impact may be higher for larger aircraft with respect to smaller aircraft [iv]. For further details on this OI, **please refer to D1.2**.

Impact on Climate

Reducing flight frequency by increasing aircraft passenger capacity through aircraft size can positively or negatively affect climate impact, depending on implementation (e.g. choice of aircraft, seating, etc.). Studies show that on short-haul routes, some current large aircraft produce higher CO_2, H2O, sulfate, soot and NO_x emissions per passenger-km over similar distances [iii]. For other current large aircraft, total emissions are lower [iv], while LTO emissions are higher. When considering a large aircraft (e.g. A330 sized) optimised for short-haul routes, CO_2, H2O, sulfate, soot and NO_x emissions per passenger could decrease with respect to emissions from currently used aircraft like the A320 (-5%) and even more compared to an A330 (-13%) [iv]. New large short-haul aircraft designs should be investigated. In an elaborate study, the flight profiles for different aircraft substitutions and emission quantities and locations can be compared in order to determine an estimate of the total climate impact due to CO_2 and non-CO_2 emissions.

Impact on stakeholders and operations

Changing aircraft size substantially for specific ranges may have a profound effect on the aircraft system. The literature describes airlines' tendency to prefer a higher flight frequency over increasing aircraft size and decreasing frequency [ii]. On highly competitive routes, an airline decreasing frequency by increasing aircraft size may economically suffer from this choice. This effect diminishes when more airlines on a specific route move towards larger aircraft. Operating costs for large aircraft optimised for short-haul flights are expected to decrease. However, purchase costs and other specific costs for these still non-existent aircraft can be estimated but are unsure.

Because ~75% of all flights are shorter than 1500km, if total passenger numbers are kept constant or slightly increased, substituting for large aircraft leads to a substantial decrease in airport and airspace traffic density. This may lead to a reduction in, for instance, congestion, flight time, delays, ATC workload and safety occurrences. Noise and emissions during LTO operation should be modelled for a large aircraft optimised for short ranges in order to determine the local impact on residents near airports. For aircraft manufacturers that are now specialized in regional or short to medium-haul aircraft, a change in direction towards larger aircraft may be a disadvantage compared to aircraft manufacturers that currently produce large aircraft. Achieving a more efficient aviation system may also lead to a loss of employment opportunities, such as in ground handling and ATM.

Finally, as the airline market is highly dynamic, it is important for airlines to have a fleet that can flexibly operate on a network changing over time. Investing in large aircraft that are usable only on high-density routes is riskier than having a larger fleet of smaller aircraft which are suitable on a wide variety of routes.

3.3.2 Preliminary assessment of the OI

Table 27: KPIs related to Trade flight frequency for aircraft size

KPI	Unit	Value	References
K1 ATR (20/100)	K	TBD	
K2.1 CO_2	kg/RPK	-2/-16%	[iii]
K2.2 NO_x	kg/RPK	-1.2%	[iii]
K2.3 H2O	Kg/RPK	-5%	[iii]
K2.4 PM	kg/RPK	TBD	
K3 Fuel flow	Kg fuel/unit time	TBD	
K4 LTO cycle	Cycles per unit time	TBD	
K12 Throughput	#pax and Kg freight	TBD	
K13 Network capacity		TBD	
K14 Network use		TBD	
K15 Network traffic concentration		TBD	
K17 A/C utilization	Revenue hours	TBD	
K19 Turnaround time	Time	TBD	
K22.1 Fleet composition		TBD	
K23 Movements	# of aircraft	TBD	
K25 Routing eff.	Added flight distance or time and number of instructions	TBD	
K26 Airport capacity	Landings/hour, takeoffs/hour	TBD	
K27 Airport traffic	# movements, pax and kg cargo/unit time	TBD	
K28 Network connectivity	# of destinations and OD pairs	TBD	
K29 Aircraft lead time	Time	TBD	
K30 Supply chain lead time	Time	TBD	
K31 Production capacity	# of ac (or parts)/unit time	TBD	
K32 Production volume	# of ac (or parts)/unit time	TBD	
K33 Travel time	Time		
K34 Passenger	RPK	TBD	

KPI	Unit	Value	References
traffic volume			
K37 Airline capacity	ASK	TBD	
K38 Airline expense	CASK	-9/-12%	[iii]
K39 Airline revenue	RASK	TBD	
K40 Passenger load factor	RPK/ASK	TBD	
K41 Cargo traffic volume	RTK	TBD	
K42 Cargo transport capacity	ATK	TBD	
K44 Cargo load factor	RTK/ATK	TBD	
K46 Time elasticity		TBD	
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	
K59.1	Passengers' acceptance	TBD	

Table 28: Advantages and disadvantages of Trade flight frequency for aircraft size

Advantages	Disadvantages
Reduction of flights	Increased schedule displacement (i.e., preferred departure/ arrival time – scheduled service time)
Reduction of airport/airspace congestion	Difficult to apply to low demand routes
Reduction of flight time	Increase demand for airport infrastructure capable of handling larger aircraft
Reduced total delays	Less flexibility in fleet utilization as larger aircraft can only be operated on busy routes
Possible reduction of safety occurrences	
Reduction of CO_2 and non-CO_2 emissions	
Possible reduction of LTO specific emission	

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3.4 Climate-optimised North-Atlantic Track System

3.4.1 Description and impact of the OI

The North Atlantic airspace (NAT) comprises about 10% of the available seat kilometres worldwide. It is considered to be the busiest oceanic airspace [i]. As a consequence of limited radar coverage over the North Atlantic airspace, an Organised Track System (OTS) has been established in order to maintain safe operations. The current NAT-OTS system is optimised with regard to wind and, therefore, fuel, and is published by Gander and Shanwick Oceanic Area Control Centres on a daily basis.

More than 50% of aviation induced climate impact is caused by non-CO_2-emissions and is characterized by a strong dependency on emission location, time and background weather situation [ii]. Therefore, climate optimised flight planning has been identified as an efficient measure in order to decrease the climate impact of non-CO_2 emissions (see section 1.3). Assuming a free-flight concept (both laterally and vertically), recent studies show that a climate impact reduction potential of up to 60% can be obtained for individual weather patterns [i], [iii].

Since a full free-flight concept may not be easy to implement in the North Atlantic airspace due to safety restrictions, a Climate-optimised North Atlantic Organised Track System can be a feasible alternative. The organised track system follows the current procedures but is optimised concerning climate impact instead of flight time, and may serve as an interim solution until free routing concepts become feasible. By optimising the North Atlantic Organised Track System with regard to climate impact, initial results by Kandur (2020) indicate potential climate impact savings in the order of 20% with related flight time penalties of about 3% for individual weather patterns. However, for some weather patterns, nearly no benefits compared to the minimum time solution have been identified [iv]. Additionally, to make the concept operational, a reliable calculation of climate change functions describing the climate impact per unit emission is required, which is fast enough to be used for flight planning [iii].

3.4.2 Preliminary assessment of the OI

Table 29: KPIs related to Climate-optimised North Atlantic Track System

KPI	Unit	Value	References
K1.1 ATR20	Relative change in temperature per unit mass of emission [%]	Up to 20% decrease	[iv]
K1.2 ATR100	Temperature change per unit mass of emission [K/kg]	TBD	
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	

Table 30: Advantages and disadvantages of Climate-optimised North Atlantic Track System

Advantages	Disadvantages
Reduced climate impact of non-CO_2 effects [iv]	Increase in flight time and cost [iv]
Large reduction of climate impact possible for small increases in cost [iv]	Not applicable for every weather situation [iv]
	Fast time calculation of climate change functions required [iii]

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

3.5.1 Description and impact of the OI

There are three main strategies when planning the airline network configuration: hub-and-spoke, point-to-point, and multi-hub [i]-[iii]. 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) markets with the same number of flight departures, fleet, and at lower total operating costs than in a complete point-to-point network [iv]. On the other hand, point-to-point strategies allow direct flights between airports, providing high convenience to passengers.

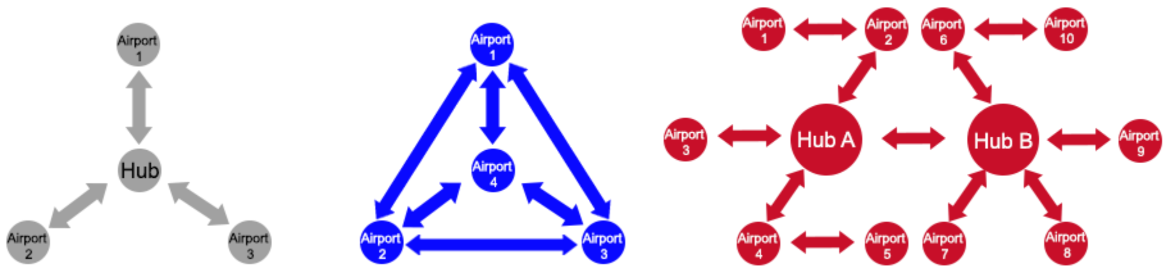

Figure 1: Hub-and-spoke (left), point-to-point (center) and multi-hub (right) configurations (fig. adapted from [xi])

Traditional flag carriers focus on providing full service to the passengers covering a large market, as efficiently as possible, to lower the per-passenger cost for the airline, hence using the hub-and-spoke model [v], [vi]. An essential aspect of providing full service from an operational perspective is that the hub-and-spoke system requires elaborated logistics to ensure reliable connections, which is a relevant cost element for the operator. On the other hand, low-cost carriers (LCCs) offer a no-frills product to the passengers, opting for a point-to-point network that connects them directly to destinations, mainly using secondary airports [vii].

Table 31: Hub-and-spoke vs point-to-point

	Advantages	Disadvantages
Hub-and-spoke	• Cover more city-pair connections with a limited number of routes and smaller fleet • Efficient use of resources, particularly labour • Higher frequency of flights • Reduced cost per available seat mile	• Frequent congestions and delays at the hub airport • Low schedule reliability • Overall longer travel times from origin to destination if not flying from/to a hub • Passenger connections at the hub • Lower aircraft utilisation
Point-to-point	• Maximises aircraft utilisation • Direct flight services • Lower fuel use per passenger • Common fleet reducing labour, maintenance, and training cost	• Widely distributed work staff • Large fleet leading to high direct operating costs • Lower frequency of flights per day

In the hub-spoke strategy, the airline can cover more airports and also concentrate its maintenance facilities and human resource services in their hub. Increasing the market share and covering demands are its main advantages. However, hub airports may face sequential delays due to unexpected situations or congestions due to complex operations. Contrarily, the point-to-point strategy offers shorter flights in terms of time and fuel consumption. We summarized the advantages and disadvantages of these two strategies.

Making improvement in an airline network topology consists of many individual decisions on whether any of two airports in the network are connected through the hub airport or not. Currently, big European hubs are operating near to their full capacity, and the same situation is happening for the main airspace sectors. When developing a strategy for airline operation, taking into account all of the limitations and constraints will be necessary. 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. Developing a mixed strategy might help some airlines improving their flexibility and reliability and create an additional opportunity to manage environmental effects in aviation. Developing a mixed operation strategy requires involving many parameters to propose a solution that meets all stakeholders' requirements.

3.5.2 Preliminary assessment of the OI

Table 32: KPIs related to Strategic planning: merge/separate flights; optimal hub-spokes/point-to-point

KPI	Unit	Value	References
K38 Airlines expenses	Relative reduction [%]	21.62% / 14.2%	[viii] [ix]
K47 Direct operation cost	Relative reduction [%]	12.8% / 8%	[ix] [x]
K15 Network traffic concentration	Relative change [%]	TBD	
K17 Aircraft utilisation	Relative change [%]	TBD	
K28 Network connectivity	Relative change [%]	TBD	
K27 Airport traffic	Relative change [%]	TBD	
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	
K59.1, K59.2	Acceptance among passengers and local communities near airports	TBD	

Table 33: Advantages and disadvantages of Strategic planning: merge/separate flights; optimal hub-spokes/point-to-point

Advantages	Disadvantages
Increase airline network flexibility	Unclear airline operations definition, demanding flexibility from work staff and passengers
Airline operations adapted to market needs	Imbalanced resource utilization
Efficient use of airline resources	Increased itinerary complexity

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4. Operational and infrastructural measures on the ground

This chapter aims to evaluate the features of seven OIs related to operational and infrastructure measures on the ground. The possibilities include upgrading the existing infrastructure (building insulation, central air conditioning, lighting, etc.), voluntary initiatives, purely E-taxiing/hybrid E-taxiing, single-engine taxiing, electrification of ground vehicles, implementation of a monitoring system for the atmospheric emissions, and renewable energy production at the airport. These OIs are expected to reduce the energy consumption at/near airports and hence the CO_2 emissions, which contribute to mitigation of aviation's climate impact. The details on the effects of these OIs and their advantages-disadvantages are elaborated.

4.1 Upgrade of the existing infrastructure according to energy efficiency criteria for the reduction of environmental impacts

4.1.1 Description and impact of the OI

Airport buildings consume significant amounts 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. BHS, elevators, etc.). There are advanced technical solutions for buildings to reduce energy consumption, CO_2 emissions, and energy wastage, while providing maximum thermal comfort and ensuring occupant safety. In general, such technologies either reduce the energy demand or increase the efficiency with which energy is used [i].

The main energy consumption in airport buildings and plants, during their operational life, are:

- building envelope and structure (insulation, glazing, airtightness and reduced thermal bridging),
- 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 environmental impacts in several ways. Below some examples of energy-efficient measures which can be adopted to make airport buildings and plants efficient and productive:

- thermal protection for enhancing the airport building envelope and structure and plants:
  - thermal insulation of the building envelope,
  - replacement of obsolete windows and doors with modern energy-efficient ones,
  - increase the airtightness of buildings (adequate ventilation of premises must be arranged along with increase of air tightness),
  - improve design details to reduce thermal bridging in the building envelope,
  - thermal control units revamping,
  - pipeline revamping;
- decrease heat losses in airport buildings:
  - restoration and sealing of inter-panel joints of the walls and ceilings, in case of panel building construction,
  - installation of additional entrance groups (halls, wind porches) with double doors,
  - installation of automatic door closers,
  - installation of heat recovery units to limit heat loss by the ventilation system and supply fresh and clean air,
  - installation of consumption monitoring systems,
  - implementation of dynamic set point systems;
- improvement and optimisation of internal heat-supply systems to decrease energy consumption:
  - thermal insulation of heating system pipelines, hot water risers, and heating system distribution networks,
  - installation of automatic individual heat points for the heat supply system,
  - installation of thermostats for heating system radiators,

- installation of balancing valves on heating system risers,
- installation of heat-and water-heating boilers with weather-compensating controls,
- use of circulating pumps for heating systems and hot water supply with built-in or external frequency converter drives,
- installation of reflective insulation behind radiators,
- hydro-pneumatic or chemical cleaning of heat supply systems, including basic equipment;

- reduction and optimisation of electricity consumption of many airport systems:
  - replacement of lamps and bulbs in internal and external lighting systems,
  - use of scheduling/occupant or daylight sensors for lighting controls,
  - use of high-efficiency electric heating/cooling equipment (heat pump),
  - optimisation of energy consumption by elevators with the installation of frequency converter drives,
  - use of frequency converters in the engineering building systems to optimise the operation of fans, pumps, and other relevant equipment,
  - installation of photovoltaic heating and power-generating systems (solar panels),
  - replacement of electric motors with more efficient motors.

The adequacy of each technology depends on the specific region, its climate conditions, and other factors.

The stakeholders involved in this OI are airport, institutional bodies, energy providers.

Despite the initial investment for infrastructure upgrading, this OI reduces the cost of the airport due to energy saved and improves the reputation of the airport.

4.1.2 Preliminary assessment of the OI

Table 34: KPIs related to the upgrade of the existing infrastructure according to energy efficiency criteria for the reduction of environmental impacts

KPI	Unit	Value	References
K51 Annual electricity consumption per unit of volume	kWh / WLU	TBD	
K52 Annual thermal energy consumption per volume unit	kWh / WLU	TBD	
K53 Annual electricity consumption per traffic unit	kWh / WLU	TBD	
K54 Annual thermal energy consumption per traffic unit	kWh / WLU	TBD	
K59.1, K59.2, K59.3	Acceptance among passengers, local communities near airports and the society as a whole	TBD	

Table 35: Advantages and disadvantages of the upgrade of the existing infrastructure according to energy efficiency criteria for the reduction of environmental impacts

Advantages	Disadvantages
Energy saving	High initial costs
Emissions reduction	Obtaining permits
Improving the user reputation	Structural and architectural constraints

4.1.3 References

[i] D. Kankana and D. Andrey, “Mapping of Existing Technologies to Enhance Energy Efficiency in Buildings in the UNECE Region.” *dubey2019mapping, United Nations Economic Commission for Europe*, 2019.

4.2 Voluntary initiatives to reduce CO_2 emissions

4.2.1 Description and impact of the OI

Voluntary initiatives allow any airports to measure their carbon footprint to reduce it and offset what cannot be reduced. Carrying out energy saving and environmental impact reduction interventions, investing in mitigation projects, and using certified carbon credits, are added values for all the airports that want to be protagonists in the fight against climate change.

One initiative that an airport can take to commit to reducing its CO_2 emissions is to voluntarily enroll in the Airport Carbon Accreditation program [i] This program allows airports to implement CO_2 emission management processes and obtain public recognition of their results by obtaining accreditation at the different levels of participation, which are:

- Level 1: calculation and verification of the environmental impact (carbon footprint) due to carbon dioxide emissions from sources under the direct control of the airport (scope 1 and 2 emissions), plus a written proof of the political commitment by the high management of the airport, to reduce emissions.
- Level 2: in addition to the requirements of level 1, development of a CO_2 emissions management plan with an agreed objective of reducing emissions as well as a reduction of ongoing CO_2 emissions, coming from sources under the direct control of the airport, calculated compared to an average of emissions over the past three years.
- Level 3: in addition to the requirements of level 2, evidence of a stakeholder involvement plan and extension of the airport's carbon footprint includes some scope 3 emissions that an airport can guide and influence.
- Level 3+: in addition to the requirements of level 3, the neutrality of carbon dioxide emissions for emission sources under the direct control of the airport.

For an airport, the entry point to the program means quantifying and verifying its environmental impact and demonstrating the involvement of its top management through a political commitment to reduce CO_2 emissions progressively. The highest level of participation (level 3+) concerns airports (including SEA), which are able to achieve the neutrality of carbon dioxide emissions of scope 1 and 2 through the compensation mechanism by purchasing carbon credits.

These improvements in the voluntary initiatives to reduce CO_2 are expected to contribute to the reduction of environmental impacts in several ways; some examples of interventions are:

- replacement of electricity and thermal energy production plants (e.g. turbines) with more efficient elements. Modern natural gas turbines can also run on a percentage of hydrogen fuel,
- use of district heating systems. An airport equipped with an energy production plant, can use district heating to power its users but also to power neighbouring third-party users, so as to increase the reduction of CO_2 also in the surrounding area,
- use of fuels and systems of production of electricity and heat with low environmental impact (e.g. renewable sources). The installation of plants to produce energy from renewable sources and the choice of the type of source depend strictly on the geographical and socio-political characteristics of the site where the airport is located,
- energy-saving awareness initiatives. An airport can intervene to increase awareness of the reduction of energy consumption (and therefore of CO_2 emissions) on its employees with information campaigns, training courses, incentives. In addition, it can also intervene on its stakeholders, who operate directly within the company, with awareness-raising interventions during the various meetings and with incentives,

- purchase of carbon credits. The achievement of level 3+ in the Airport Carbon Accreditation program presupposes the neutralization of the scope 1 and 2 airport emissions through the purchase of carbon credits from certified energy plants,
- development of procedures to optimise production processes. The study of new methods and the improvement of those existing in the production and management of production processes allows constant monitoring and constant improvement of energy performance. For example, by adopting ISO14001 and ISO50001 management systems that guarantee continuous verification audits,
- energy-saving interventions on buildings. The consumption of electricity and thermal energy of the various airport buildings make up an important portion of the total airport consumption, therefore intervening to reduce these consumptions can lead to a significant reduction in airport CO_2 emissions,
- installation of energy meters and consumption analysis. It is important to know where, how and when energy is consumed inside the airport in order to be able to intervene in a targeted way and obtain maximum energy savings,
- installation of led lighting. The electricity consumed for airport lighting is an important portion of the total airport electricity consumption, the installation of LED lights, for example, allows to obtain a significant energy saving,
- promoting electric mobility. The use of electric cars saves the direct emissions generated by internal combustion engines.

The stakeholders involved in this OI are airports, energy providers, institutional bodies, third parties working at the airport.

Besides the initial investment necessary to realize the interventions, this OI has a positive impact on the airport in terms of cost reduction because of the energy saved and in terms of reputation.

4.2.2 Preliminary assessment of the OI

Table 36: KPIs related to voluntary initiatives to reduce CO_2 emissions

KPI	Unit	Value	References
K2.1 - Emissions	Tonnes	TBD	
K53 Annual electricity consumption per traffic unit	kWh / WLU	TBD	
K59.3	Societal acceptance	TBD	

Table 37: Advantages and disadvantages of voluntary initiatives to reduce CO_2 emissions

Advantages	Disadvantages
Energy saving	Initial costs
Emissions Reduction	Resistance to change
Increased reputation	Operational/processes drawbacks
Improvement of air quality	

4.2.3 References

[i] Airport carbon accreditation Report, Available: www.airportcarbonaccreditation.org [Accessed: 20-July-2020].

4.3 E-taxi (tow truck or tug wheel) and hybrid taxi

Aircraft engines are very inefficient for use for propulsion on the ground. Thermodynamically a lot of heat is wasted, and propulsive efficiency is low due to a low mass flow, and the limited amount of air needs to be accelerated a lot to gain sufficient thrust. Using wheel-based propulsion systems could be much more efficient.

4.3.1 Description and impact of the OI

There are two main concepts for moving an aircraft on the ground without using the aircraft engines. One uses a tow truck to move the aircraft, and the other is based on mounting an electric motor to drive one or more of the landing gear wheels. Additionally, a combination of the two is a potential solution that has not yet been tested. A general limitation of both systems is that the engines of an aircraft need to be running for about three minutes before take-off power can be applied. Similarly, the engines must be running for a few minutes after landing before they can be shut down, limiting the time the ground movement system can save fuel.

Using the first option, a tug such as the TaxiBot system is a ground-based solution and will only work in airports where a tug is available and for aircraft that are compatible with that tug. It functions mostly the same as tow trucks already do in current operations, though a system like TaxiBot allows the pilot to control the system by moving the nose wheel or connecting through a ARINC bus on Airbus aircraft. Controlling acceleration from the cockpit is more complicated. Especially at larger airports, with larger taxi times, engines can be started late during taxiing and fuel can thus be saved. The APU needs to be running to provide electrical power and air-conditioning and bleed air to start the engines, reducing the fuel savings slightly. Before the aircraft can take off, close to the departure runway, the tug must be disconnected and drive back to the terminal or the arrival end of a runway. Current trials do not use TaxiBot for taxi-in, as coupling the tug after landing near the runway exit would cause congestion and potential safety hazards. The TaxiBot must use the taxiways when driving back without an aircraft, and can thus cause issues with aircraft heading towards the runway. A more structural issue is that the nose gear is generally not designed for the forces being generating by towing the aircraft close to maximum take-off weight, so acceleration and speed are limited.

An alternative concept is using an onboard electric motor to power the aircraft. This solution requires the aircraft to install a new system, but it will work at any airport. However, the benefits of such a system are best exploited in an airport with large taxi distance and short flights, where fuel penalty due to the increased aircraft weight remains limited. Steering will happen the same way as it does with normal engine-based taxiing, though differential steering in case of the motors on the main wheel can also be used to limit the steering forces. The nosewheel does not have enough traction to be used for taxiing at normal speeds. As well as the tug-based system, with this system, engines can be started later in the taxi phase, and the APU will need to be running, not only for the normal electric systems, air conditioning and starting the engines, but also to provide electricity for the taxiing. Current APU's on aircraft cannot provide enough power to taxi at normal speeds and modifying these APU's would be expensive and add weight, which is also an issue if batteries would be installed. A final issue is that the system must be disengaged when the aircraft takes off and lands and have a safety system to ensure this.

A final solution, not currently being tested, is a hybrid solution. In this case, wheel-mounted motors receive power from the tug on the nose and provide extra traction from the main wheels, allowing higher acceleration and taxi speeds than either solution on its own. The tugs could be designed somewhat lighter as they do not need to provide all the traction. An extra complication is that, next to connecting a tug, a high-power electrical connection must also be made between the tug and the aircraft, which would require either an operator or some complex robotic automation.

4.3.1 Preliminary assessment of the OI

Table 38: KPIs related to E-taxi (tow truck or tug wheel) and hybrid taxi

KPI	Unit	Value	References
K.3 Fuel flow	Fuel [% during taxiing]	50-85% decrease	[i]
K27.1 Airport traffic	Movements	+1 movement for each tow	[ii]
K.3 Fuel flow	Fuel during flight	~10kg per flight	[iv]
K59.1, K59.2, K59.3	Acceptance among passengers, local communities near airports and the society as a whole	TBD	

Table 39: Advantages and disadvantages of E-taxi (tow truck or tug wheel) and hybrid taxi

Tug based

Advantages	Disadvantages
Limited aircraft modifications	Tugs must be available
No additional aircraft weight	Somewhat limited speeds
	Coupling and de-coupling close to runways
	Opposite traffic on taxiways

Wheel based

Advantages	Disadvantages
No airport modifications or investments	Added weight to aircraft weight
No (de-)coupling required	Limited speeds

Hybrid

Advantages	Disadvantages
High taxi speeds when both tug and on-board system are available	Complex power connection required

4.3.2 References

[i] "Schiphol and partners to begin sustainable aircraft taxiing trial." Schiphol Newsroom. https://news.schiphol.com/schiphol-and-partners-to-begin-sustainable-aircraft-taxiing-trial/ (accessed Aug. 12, 2020).

[ii] E.V.M. van Baaren, "The feasibility of a fully electric aircraft towing system," M.S. thesis, ATO, TU Delft, Delft, Netherlands, 2019. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3Ac47a1e3e-8d3b-4eda-8b3b-134ae29f6af9?collection=education

[iii] "Air India first in the world to use Taxibot on a commercial flight." The Economic Times, Industry. https://economictimes.indiatimes.com/industry/transportation/airlines-/-aviation/air-india-first-in-the-world-to-use-taxibot-on-a-commercial-flight/ai-first-to-use-a-taxibot-on-a320/slideshow/71594280.cms (accessed Aug. 12, 2020).

[iv] "TaxiBot." Smart Airport Systems SAS. https://www.smart-airport-systems.com/solutions/taxibot/ (accessed Aug. 12, 2020).

[v] C. Wijnterp, P.C. Roling, W.D. Wilde, and R. Curran, "Electric Taxi Systems: An operations and value estimation" in 14th AIAA Aviation Technology, Integration, and Operations Conference. 2014.

4.4 Single engine taxiing

4.4.1 Description and impact of the OI

One of the easiest ways to reduce fuel burn on the ground is by turning off one (or more) of the engines after landing. While this can almost half the emissions on the ground, the remaining engines need to run at a higher thrust setting, causing concerns over blast force from the engines. Also, asymmetric thrust conditions can cause issues in strong winds or slippery pavement conditions. On taxi out, the application of this concept is less likely, as engines need to be running for about three minutes before being pushed to take-off thrust.

On taxi in, according to [iii], carbon emission can be reduced by 20-40% and NO_x emissions from 10-30%. According to [ii], in the US, there can also be significant savings on taxi out, due to large departure queues. More efficient departure queueing method as utilized in Europe, by keeping aircraft at the gate or towing them to a waiting stand, would lead to more savings.

4.4.2 Preliminary assessment of the OI

Table 40: KPIs related to Single engine taxiing

KPI	Unit	Value	References
K3 Fuel flow per taxi	Tonnes %	20-40% decrease	[i]
K2.1 CO_2 per taxi	Tonnes %	20-40% decrease	[i]
K2.2 NO_X per taxi	Tonnes %	10-30% decrease	[i]
K59.2	Acceptance of local communities near airports	TBD	

Table 41: Advantages and disadvantages of Single engine taxiing

Advantages	Disadvantages
Standard operating procedure	Increased jet blast danger
Easy on taxi in	Asymmetric thrust
	Taxi out is difficult

4.4.3 References

[i] "Iberia Airlines Taxiing Program To Reduce Emissions At ORD." Aviation Pros. https://www.aviationpros.com/airports/airports-municipalities/article/10467486/singleengine-taxi-program-will-reduce-emissions-and-save-fuel (accessed Aug. 12, 2020)

[ii] V. Kumar, L. Sherry, and T. Thompson. "Analysis of Emissions Inventory for 'Single-engine Taxi-out'Operations." in International Conference on Research in Air Transportation (ICRAT-2008). 2008.

[iii] "Increasing single-engine taxi operations or taxi on only inboard engines of 4-engine aircraft." NLR. https://www.nlr.org/areas-of-change/increasing-single-engine-taxi-operations-taxi-inboard-engines-4-engine-aircraft/ (accessed Aug. 12, 2020).

4.5 Electrification of ground vehicles and operations

4.5.1 Description and impact of the OI

Electric mobility [i] represents an important aspect for the passage of an airport to the decarbonization of its processes and, albeit with a booming market and interesting incentive policies, it also represents an important challenge in terms of infrastructure, methods and recharging times, availability of vehicles and new ways of using the vehicles by users.
The first challenge concerns the capacity and recharge times of the batteries of electric vehicles which, when compared to the normal performance of diesel vehicles, show their limits, even if the development is constantly growing.
A further challenge concerns the infrastructure network necessary for the installation of the charging points, which requires a strong initial commitment in terms of costs and interventions. For an airport, the transition to electric mobility does not refer only to the replacement of traditional vehicles (cars, vans, etc.) but presupposes the replacement of a series of specific equipment for airport activities (GSE - Ground Service Equipment) which often do not have valid alternatives on the market. The move to electric mobility will also imply a different approach to the use of cars, giving more incentive to the use of car-sharing and increasingly freeing the user from the concept of "own means", this will entail a transition period in which traditional users will have to accept and adapt to the new modes of mobility.

Ground Service Equipment (GSE) is critical to the success of airport operations and fast aircraft turnaround. Not only does GSE electrification save money on diesel and maintenance costs, it also contributes positively to the respiratory health of airport workers and surrounding neighbourhoods and supports efforts to reduce carbon footprints.

Though the benefits are clear, airports often have limited spare electric capacity and find it cost-prohibitive to upgrade their electric services. This is where a carefully crafted energy-efficiency strategy can make a strong positive impact. Airports are known to be large consumers of electric power for air traffic operations and terminal needs, including check-in desks, escalators, baggage handling and conveyor belts, service/visitor lifts, shops and restaurants. Targeted energy-efficiency measures applied to nearby circuits can free up the capacity needed for these new electric loads. Smart charge management systems can ensure that most charging is completed when electricity is least costly, usually overnight, as other airport electric loads are low during this time.

Electric vehicles also provide an opportunity to advance airports as infrastructure assets for electric generation. Electric buses and cars, already part of airport land transport, can be linked together to transfer power from one vehicle to another, or to act as a localized battery pack providing newly generated electricity.

The stakeholders involved in this OI are airports, energy providers, institutional bodies, third parties working at the airport, passengers.

Besides the initial investment necessary to realize the electric mobility, this OI has a positive impact on the airport in terms of cost reduction because of the energy saved and in terms of reputation.

4.5.2 Preliminary assessment of the OI

Table 42: KPIs related to the electrification of ground equipment vehicles and operations

KPI	Unit	Value	References
K2.1 - Emission	CO_2 tons	TBD	
K53 Annual electricity consumption per traffic unit	KWh / WLU	TBD	
K51 Annual electricity consumption per unit of	kWh / WLU	TBD	

KPI	Unit	Value	References
volume			
K2.1 Emissions per Km	CO_2 Kg / Km	TBD	
K59.1, K59.2, K59.3	Acceptance among passengers, local communities near airports and the society as a whole	TBD	

Table 43: Advantages and disadvantages of the electrification of ground equipment vehicles and operations

Advantages	Disadvantages
Energy saving	Initial costs
Emissions reduction	Lack of electric alterative on the market
Increased reputation	Little battery autonomy
Take advantage of economic incentives	
Improvement of air quality	

4.5.3 References

[i] Electrification Empowers Tomorrow's Airports, Available: www.wsp.com [Accessed: 20-July-2020].

4.6 Implementation of a monitoring system for the atmospheric emissions

4.6.1 Description and impact of the OI

This chapter aims to provide first an overview of the emissions monitoring system of a facility source like airports to define a possible trade-off between the system of monitoring and its compliance with environmental goals like emissions reductions. The second objective is the use of measured data for airport operators in the definition of KPIs in order to have the possibility to introduce corrective actions if the requirements are not easily respected.

In Europe, the majority of civil airports are located in an urban context, with several citizens exposed to a high level of noise and emissions of pollutants [ii]. The atmosphere in the vicinity of airports, is a complex system where different sources contribute to local air quality. In many cases, these sources could be related to airport activities and external elements like roads, buildings, and factory plants with whom an airport shares the principal chemical substances emitted (i.e., Particulate matters, Nitrogen dioxide, Carbon Monoxide). There are also some specific aircraft-related pollutants to study like Aldehydes compounds [i]. but they should be measured with specific analysis and are not easy to be included in a monitoring device.

Separating airport emissions from other sources is the main issue in managing this externality at the airport level. Compared to airport environmental noise, aircraft emissions of pollutants are more challenging to identify for this multi-source conditions but also for a less defined procedure in developing a monitoring system. While a Noise monitoring system is planned following specific guidelines and rules (i.e.: noise devices are placed under Airport SID and are connected with ATM), a monitoring system for atmospheric emissions has fewer conditions related to aircraft and airports. The OI associated with the implementation of an emission monitoring system should be based on few general parameters such as accuracy of the source, identification of the location, type of control unit, substances investigated (described below), and integrated according to each different airport conditions.

Here we present a synthetic procedure for this OI related to ground infrastructure.

4.6.2 Preliminary assessment of the OI

Generally, an airport emissions monitoring system could be defined by a limited number of fixed monitoring stations placed in significant zone/zones in order to analyse some specific sources like ground operations and GSE (Ground Service Equipment) and measure the global air quality of the airport.

In the first phase, the main objective for the monitoring system's definition is to identify the best available position for the devices in order to minimise the contribution of sources not belonging to the airport. The preliminary actions to this first phase will focus on the analysis of the best place where the highest concentrations gradient could be measured with respect to an atmospheric monitoring station placed in the territory surrounding the airport but not influenced by it. This preliminary phase could be implemented both with the use of temporary stations and mathematical models.

In the second phase, the main objective for the definition of the monitoring system is the characterization of the airport source to be investigated. One single monitoring device could cover all the airport-related sources, but it would also be possible to separate the aircraft emissions from GSE or even road traffic induced by airports.

As a matter of fact, after completing the construction of the monitoring system layout, it is necessary to proceed with the selection of the type of monitoring stations. According to EPA (Environmental Protection Agency) [i], a stationary source emissions monitoring is composed of four elements: indicators of performance, measurement techniques, monitoring frequency, and averaging time.

There is a vast literature regarding the characteristic of continuous emissions monitoring systems [iii], [iv], but there is not a specific procedure for transport infrastructure like airports. So, the best standard available in the regulatory requirements is contained in EU Directive 2008/50 [vii] (modified by EU Commission Directive 2015/1480) regarding air quality in Europe.

The emissions limit set by EU Directive could be the KPI for the evaluation of this OI.

Averaging Period	Limit value	Margin of tolerance	Date by which limit value is to be met
Sulphur dioxide			
One hour	350 µg/m³, not to be exceeded more than 24 times a calendar year	150 µg/m³ (43 %)	— (1)
One day	125 µg/m³, not to be exceeded more than 3 times a calendar year	None	— (1)
Nitrogen dioxide			
One hour	200 µg/m³, not to be exceeded more than 18 times a calendar year	50 % on 19 July 1999, decreasing on 1 January 2001 and every 12 months thereafter by equal annual percentages to reach 0 % by 1 January 2010	1 January 2010
Calendar year	40 µg/m³	50 % on 19 July 1999, decreasing on 1 January 2001 and every 12 months thereafter by equal annual percentages to reach 0 % by 1 January 2010	1 January 2010

Figure 2. Limit values for SO_2 and NO_2 according to EU 2008/50 Directive

Data collected from the monitoring stations are recorded in specific servers and elaborated before being published. A weather monitoring station is also necessary to correlate substance concentrations with the weather condition.

It should be noted that the procedure needs a high cost of maintenance and could not be an option for smaller airports. So, another approach focuses on mobile measure campaigns to analyse a specific operational scenario or different pollutants. It could be useful if economic constraints don't allow the implementation of a stationary continuous system. This method could be more flexible and even more precise when a specific category of pollutants is analysed. Unfortunately, these campaigns are influenced both by the specific period when they are done and the limited interval of time among the measurements, so it is necessary to plan a specific number of campaigns to cover the annual dynamics in pollutant concentration trends. All these aspects specify that every airport should implement its emissions monitoring system, considering a significant amount of variables taking into account environmental and economic parameters.

Table 44: KPIs related to the implementation of a monitoring system for the atmospheric emissions

KPI	Unit	Value	References
K.2.1.1 SO_2	µg/m3 daily mean value	< 125	[vii]
K.2.1.2 CO	mg/m3 daily mean value	< 10	[vii]
K.2.1.3 PM_{10}	µg/m3 daily mean value	< 50	[vii]
K.2.1.4 NO_2	µg/m3 hourly mean value	< 200	[vii]
K59.3	Societal acceptance	TBD	

Table 45: Advantages and disadvantages of the implementation of a monitoring system for the atmospheric emissions

Advantages	Disadvantages
Improvement in the management of air quality in the proximity of airport	High costs of maintenance
Monitoring methods based on airport characteristic	Not standardized procedure
Possibility to evaluate different actions for mitigation	Not easy to integrate in airport management procedures

4.6.3 References

[i] EEA, European Environmental Agency, European Aviation Environmental Report 2019. Available: https://ec.europa.eu/transport/sites/transport/files/2019-aviation-environmental-report.pdf [Accessed: 20-July-2020].

[ii] FAA, Federal Aviation Administration Office of Environment and Energy: Hazardous air pollutants (haps) associated with aircraft, airports, and aviation, July 2003: https://www.faa.gov/regulations_policies/policy_guidance/envir_policy/media/HAPs_rpt.pdf [Accessed: 20-July-2020].

[iii] EPA, Environmental Protection Agency. Available: https://www.epa.gov/emc/performance-specifications-and-other-monitoring-information; [Accessed: 20-July-2020].

[iv] J. Watson, J. Chow, X. Wang, S. Kohl, "Overview of real-world emission characterization methods" *Developments in Environmental Science Vol. 11, P. 145-170*, 2012.

[v] K. Clifford, A. Robinson, D. Miller and M. Davis "Overview of Sensors and Needs for Environmental Monitoring", *Sensors Volume 5 Issue 1* 2005.

[vi] J. Jahnke, "Continuous emission monitoring", *John Wiley & Sons;* 2000

[vii] EU Directive 2008/50 https://eur-lex.europa.eu/legalcontent/en/ALL/?uri=CELEX%3A32008L0050 [Accessed: 20-July-2020].

4.7 Renewable energy produced at airport

4.7.1 Description and impact of the OI

The safe and efficient operation of flights at airports of all sizes requires considerable energy use, making it a significant operating cost. The most common energy uses at the airport level are:

- Airport terminal: lighting, heating, and cooling (air conditioning) and appliances (baggage handling systems, terminal bridges);
- Airport airside: runway lighting, auxiliary power units (APUs) and aircraft ground energy systems (AGES), ground vehicles (from airport operators, ground-handling companies and firefighting services), and airside facilities such as hangars.

For a detailed analysis of energy consumed at the airport, we refer to S.O. Alba and M. Manana, 2016 [i].

One of the possible measures to reduce greenhouse gas (GHG) emissions is to install renewable energy generators on site. The renewable energy options that can be produced at the airport level are solar, wind, biomass, hydro, and geothermal. The practical application and development of these renewable energy options depend mainly on the characteristics of the individual airport, such as its physical settings (e.g. geography, geology, and climate), and its operational and economic reality. These measures should be combined with energy conservation measures from operational and infrastructural perspectives (e.g. night-time shut down, building insulation). For a complete survey of renewables at the airport level, we refer to the ICAO's Eco-Airport toolkit [ii].

ACI Europe formally committed to making the European airport industry reach the net-zero for carbon emissions by 2050. The importance of renewable energies in this transition is confirmed by the agreement signed between ACI Europe and RE-Source Platform, the European alliance of stakeholders for corporate renewable energy sourcing [iii]. In this context, building renewable energy generators is a way to gain a "green reputation" for an airport, for instance, through the Airport Carbon Accreditation Programme [iv]. By reducing the GHG emissions, renewables have also a positive impact on the air quality in the airport vicinity. From an operational perspective, the production of renewables at the airport enhances energy security. The energy generated on-site with renewables provide a risk mitigation measure to the airport and its wide range of users, making shortages and adverse effects on operational performance less likely to occur. However, part of the staff should be trained to perform the continuous maintenance needed to ensure the correct operation of these technologies. Expanding on the economic side, one of the advantages is that the energy produced at the airport is independent of the increasing price volatility of fossil fuels. Despite the initial investment, such a technology might have a positive economic impact on the long-term. Finally, a crucial point while installing renewable energy generators on-site is to consider operational safety. For instance, photovoltaic systems may present challenges with regards to solar glare, and wind turbines may penetrate the navigable airspace in close vicinity to airports and generate interference issues with safety-critical communication, navigation and surveillance infrastructure.

4.7.2 Preliminary assessment of the OI

Table 46: KPIs related to Renewable energy produced at airport

KPI	Unit	Value	References
K1.1 ATR20	K or °C	TBD	
K1.1 ATR20	K or °C	TBD	
K2.1 Emissions of CO_2	Tonnes/year	TBD	
K2.2 Emissions of NO_x	Tonnes/year	TBD	
K2.4 Emissions of PM	Tonnes/year	TBD	

KPI	Unit	Value	References
K2.1 Emission of CO_2	kg/passenger	1.5 kg CO_2/passenger	[iv], [v]
K2.1 Emission of CO_2	Tonnes	0.169 million	[iv], [v]
K55 Energy expenses	€	TBD	
K56 Energy usage	kWh/passengers[3] year	9.29 (average)	[vi]
K11.1 Accident rate -ground and TMA	% change in count of events	TBD	
K59.3	Societal acceptance	TBD	

Table 47: Advantages and disadvantages of Renewable energy produced at airport

Advantages	Disadvantages
GHG emission reduction	High initial costs (i.e. for construction works and staff training)
Improvement of air quality in the proximity of airport	High costs of maintenance
Enhancement of the energy security	Potential effects on operation safety
Reduction of dependence of energy commodities with volatile prices	
Reputation gain	

4.7.3 References

[i] S.O. Alba and M. Manana, "Energy Research in Airports: A Review". Energies. 2016.

[ii] ICAO, "A Focus on the production of renewable energy at the Airport site - ECO AIRPORT TOOLKIT" https://www.icao.int/environmental-protection/Documents/Energy%20at%20Airports.pdf

[iii] ACI EUROPE, "ACI EUROPE partners with RE-Source to accelerate clean energy transition at Europe's airports & deliver NetZero2050." [Online]. Available: https://www.aci-europe.org/press-release/202-aci-europe-partners-with-re-source-to-accelerate-clean-energy-transition-at-europes-airports-a-deliver-netzero2050.html. [Accessed: 08-May-2020].

[iv] Airport Carbon Accreditation, 2018, Airport Carbon Accreditation Annual Reports.

[v] EASA, EEA, EUROCONTROL, "European Aviation Environmental - Report 2019". 2019. https://ec.europa.eu/transport/sites/transport/files/2019-aviation-environmental-report.pdf

[vi] Costa, L. M. Blanes, C. Donnelly and M. M. Keane "Review of EU airport energy interests and priorities with respect to ICT, energy efficiency and enhanced building operation". Proceedings of the Twelfth International Conference for Enhanced Building Operations, Manchester, UK, October 23-26, 2012. 2012.

[3] International, domestic and direct transit.

5. Operational measures at regulatory level

The operational measures at regulatory level are considered from two aspects. The first measure is to limit “climate unfriendly” airport operations by introducing, for instance, market-based measures, operating restrictions, route clearance/restricted airspaces for climate-sensitive regions, etc. These measures are expected to reduce the climate impact of aviation from both CO_2 and non-CO_2 effects. The second OI is to use environment scoring, which allows prioritizing more climate-friendly aircraft operations/routes/procedures/types. These OIs are regional dependent and relying on public engagement. More details on these two OIs are described in this chapter.

5.1 Limit "climate-unfriendly" aircraft operations

5.1.1 Description and impact of the OI

The climate impact of a single flight depends on a combination of route, flight profile (combined with the flight trajectory), and aircraft properties together with the atmospheric properties along the flight trajectory. While the impact of CO_2 emissions is independent of location (longitude, latitude and altitude), the impact of non-CO_2 emissions such as NO_x depend on location and flight trajectory, time of day and atmospheric conditions. The amount of CO_2 and non-CO_2 species emitted also depends on aircraft and engine type and thrust setting, where the latter depends on aircraft weight, speed and altitude [i].

To reduce the climate impact of the non-CO_2 emissions of aircraft, regulations could be implemented that promote more climate-friendly aircraft operations which include all relevant aspects of the operation and local state of the atmosphere. To this end, the impacts of both CO_2 and non-CO_2 emissions need to be determined and traded off for specific aircraft operations at various atmospheric conditions. Several options could be envisaged to promote climate-friendly aircraft operations, which are summarized below. However, they strongly depend on the availability and reliability of methods and tools to accurately determine the impact of non-CO_2 emissions for any part of a flight. This includes in particular high-resolution data on atmospheric conditions allowing the precise location of contrail-formation areas. For details on these options, see [i].

1. A market-based mechanism, where emissions or climate impact will be valued and offset (or charged) or limited to a maximum value through regulation
2. Operating restrictions and regulations for aircraft operations in certain parts in the atmosphere at certain timeframes. Flight restrictions are adapted on the current state of the local atmospheric conditions. Flights could, for example, be restricted to lower altitudes (see Section 2.6) or to day time to avoid the negative climate impact of contrails formed at night.
3. Route clearance/restricted airspaces for climate-sensitive areas, where the local atmospheric conditions are not known (see Section 2.10).
4. Regulations imposing direct specific flight procedures on some flight segments. Examples are obligating CCO/CDO operations (see Section 2.2)

Note: all 4 options will probably lead to different options to mitigate non-CO_2 impact.

Impact on Climate

The impact of this OI varies per location, and per targeted mitigated emission type. The climate impact of CO_2 is independent of location and time of emission and therefore, putting constraints on aircraft flight trajectories will have no effect on reducing CO_2, on the contrary, flying diversions will increase fuel burn and thus CO_2 emissions. However, since the climate impact of NOx and contrail formation is strongly dependent on the location of emission, time of day, and atmospheric conditions, [ii], the mitigation of these effects will depend on the specific location (region) where this OI is implemented.

Overall, the climate impact of CO_2 and non-CO_2 emissions will be reduced, because climate unfriendly aircraft operations are limited whereas more climate-friendly operations are prioritized. Additionally, this OI will encourage fleet renewal, which will lead to an even larger positive impact on climate change over the longer term.

Impact on operations and stakeholders

The implementation of the above-mentioned regulations will stimulate stakeholders to foster climate-friendly aviation. Local governments and supranational regulatory bodies will take action to implement regulations to regulate climate unfriendly aircraft operations. ATM organisations adapt their infrastructure to monitor local (climate) conditions and facilitate a more flexible (time and space) 4D flight paths. OEM and airlines need to equip their aircraft with relevant instrumentation.

Airports and airlines need to build in more flexibility in their flight schedules in case of (larger) detouring. By doing so, responding stakeholders, such as airports and ATM, have the ability to adapt their operations to the local (climate-relevant) conditions and facilitate/enforce these climate-friendly regulations. The updated Air traffic management (and Air navigation providers) equipment and procedures seek to determine the local state of the atmosphere and predict the impact of a flight passing through as compared to reference thresholds for e.g. contrail formation and adjust operations accordingly**.** Additionally, OEM's as responding stakeholders could aim to produce/retrofit aircraft that meet or are adaptable to the new climate standards. In addition to existing economic pressures to minimise costs, as impacted airlines' stakeholders could consider to:

1. Adjust their fleet towards more climate-friendly aircraft
2. Reassign aircraft to flights taking into account the regulatory aspects, or;
3. Reroute flights by adjusting hub and spoke systems and thereby avoiding climate-sensitive areas.

Operating climate-friendly aircraft may benefit airlines to gain a competitive edge if flights are prioritized based on the impact on climate-sensitive airspace. The changes supported by this OI will especially affect passengers, as actual flight times may often vary from scheduled flight times and hence require more flexible transit times. Residents near airports may be affected because actual landing times may differ significantly from the scheduled one and time-wise prediction of annoyance and respite hours by residents shows more spread. Relevant information needs to be fed to both government (for administrative purposes) and airlines to guide their operations. Selection of the right KPI's and deep understanding of the transport and chemical characteristics of the atmosphere is key for proper traffic management.

5.1.2 Preliminary assessment of the OI

In this section the KPI's that can be used to assess the success of this OI are listed. It should be noted that this OI combines multiple other OI's, and therefore no specific values can be given without assessment of the combination of the OI's involved.

Table 48: KPIs related to Limit "climate-unfriendly" aircraft operations

KPI	Unit	Value	References
K1.1 ATR20	K or °C	TBD	
K1.2 ATR100	K or °C	TBD	
K2.1 CO_2	kg	Dependent on fuel type	
K2.2 NO_x	kg	Location and time (of day) dependent	
K2.3 H2O	kg	Location and time (of day) dependent	
K2.4 PM	kg	Location and time (of day) dependent	
K3 – Fuel flow	Kg fuel	Decreases if climate friendly operations are more efficient, but increases if routes are extended for the benefit of non- CO_2 emissions reductions	
K7 Route efficiency	km	Decreases if climate friendly operations are more efficient, but	

KPI	Unit	Value	References
		increases if routes are extended for the benefit of non- CO_2 emissions reductions	
K8 Sulphur content	Mixing ratio of sulphur in fuel	Dependent on fuel type	
K9 Sustainable aviation fuel (SAF) use	Percent of SAF used	Limit set at 50% so that aircraft do not modifications	[iii]
K10.1 Accident rate - airborne	% change in count of events	TBD	
K11.1 Accident rate - ground and TMA	% change in count of events	TBD	
K21.1 On-time performance (due to detouring)	Delta in minutes	TBD	
K24 Airspace capacity	# of movements/unit time	TBD	
K33 Travel time	Delta in minutes	TBD	
K38 Airlines expense	CASK	TBD	
K58 Controllers' workload	Relative variation of number of operations in unit time [%]	TBD	
K59.1, K59.3	Passengers' and societal acceptance	TBD	

Table 49: Advantages and disadvantages of Limit "climate-unfriendly" aircraft operations

Advantages	Disadvantages
Reduced CO_2 and non-CO_2 impact	Variable impacts per location may lead to competitive distortions
Reduction of contrail formation	Fleet adaptation
Motivates and stimulates mindset of stakeholders for more direct actions toward climate-friendly operations.	Airlines, ATM and airports need to adapt and prefer reduced climate impacts over costs
Provides tools to stakeholders involved to trade-off their investments/decisions and to help them take responsibility for the consequences of their operations.	Schedule and strategic planning needs to become more flexible to cater for detouring/delays
	Cost to set up a monitoring system to map the atmospheric state

5.1.3 References

[i] ClimOp Consortium, "D1.2 – Inventory of operational improvement options," 2020

[ii] V. Grewe, T. Champougny, S. Matthes, C. Frömming, S. Brinkop, O. Søvde, E. Irvine, L. Halscheidt, "Reduction of the air traffic's contribution to climate change: A REACT4C case study," *Atmos. Environ.*, vol. 94, pp. 616–625, Sep. 2014

[iii] Sustainable Aviation, "Sustainable Aviation Fuels Road-Map", 2020

5.2 Environmental scoring

5.2.1 Description and impact of the OI

Implementing this OI allows prioritizing aircraft operations/routes/procedures/types which are (highly) climate-friendly over those that are less climate-friendly. By prioritizing climate-friendly operations and aircraft as well as public awareness, less climate-friendly operations will be phased out in the long term.

Environmental scoring promotes monitoring, objectivity and information purposes to allow potential travellers to better guide their decision to travel and for airlines to adopt a more climate-friendly fleet and operations. The environmental scoring OI is geared towards information for the general public, and airlines to reveal their relative position/rank. Scoring implies that KPIs are represented in a format easily understandable and transparent, for instance, through one overall score for all KPIs combined.

In this way, the general public will be involved and continuously informed. This allows transparency, and it allows passengers to better guide their decision to travel. Within environmental scoring, KPI's can be gathered KPI's for the purpose of guiding operations. Implementation can take place through the following three concepts:

1. Rating certain flight operations with respect to CO_2 climate impacts, non-CO_2 climate impacts, (and environmental, thus LAQ related emissions and noise),
2. create structure/methodology to facilitate this,
3. benefit airlines or flights with better scores through differentiating levies or granting preferred (time)slots,
4. generating insights for the general public and passenger to opt for better scoring flights

Impact on Climate

On the short term, flights with a higher environmental score will be allowed priority over flights with a lower environmental score. As the assignment of environmental scores is a transparent process, the general public and passengers can inform themselves, and the flights with higher environmental scores will gain more positive attention. Therefore, the public will also favour flights with higher environmental scores if 'flygskam[4]' becomes more widespread. To assess short term temperature response due to emission reductions, ATR20 can be used. For long term climate effects ATR100 would be appropriate [ii].

Impact on operations

On the long term, by benefitting flights with better environmental scores over those with lower environmental scores, climate-unfriendly aircraft and flights will be phased out and make way for even more climate-friendly aircraft and operations. This stimulates technological advancement, and on the long term, a larger impact is expected. It must be noted, however, that the impact is dependent on the region and market in which the flights are scored. The regulatory bodies and acting stakeholders should make sure that a level playing field is ensured when this OI is implemented and deployed.

[4] "Flygskam ("flight shame" in Swedish) is the name of an anti-flight movement that originated in Sweden as early as 2017 and later spread in other European countries. Flygskam encourages the use of means of transport with a lower climate impact than aviation."

Impact on stakeholders

In order for this OI to be implemented effectively, the Government, ATC and airports need to cooperate. They are the Acting stakeholders for this OI. These stakeholders also carry responsibility for a level playing field for all airlines. Airlines are the Responding stakeholders, and they need to be able to adapt to the new scores. This might need to be nudged or supported by regulatory bodies to move it in the right direction in the start-up phase. The affected stakeholders that experience the losses and the gains from this OI are the OEMs, passengers, the general public and the residents near airports.

5.2.2 Preliminary assessment of the OI

Table 50: KPIs related to Environmental scoring

KPI	Unit	Value	References
K2.1 CO_2	kg	Dependent on fuel type	
K2.2 NO_x	kg	Location and time (of day) dependent	
K2.2 H2O	kg	Location and time (of day) dependent	
K2.4 PM	kg	Location and time (of day) dependent	
K3 Fuel flow	Kg fuel		
K8 Sulphur content	Mixing ratio of sulphur in fuel	Dependent on fuel type	
K9 Biofuel use	Percent of biofuel used	Limit set at 50% so that aircraft do not modifications	[i]
K1.1 ATR20	Average temperature response over 20 years		
K1.2 ATR100	Average temperature response over 100 years	-32% for 0% cost increase if entire A330-200 fleet is replaced by redesigned aircraft and for climate optimised cruise operations	[ii]
K7 Route efficiency	Measure of detour wrt great circle distance	TBD	
K59.1, K59.3	Passengers' and societal acceptance	TBD	

Table 51: Advantages and disadvantages of Environmental scoring

Advantages	Disadvantages
Flight characteristics based operating restrictions will reduce CO_2 and non-CO_2 emissions	Variable impact per region and operation which makes it difficult to generalize
Engagement of travelers in the transition towards a climate-friendly aviation	Dependency on public engagement
Insights in impacts of various flight operations	It must be ensured that airlines do not trade

Advantages	Disadvantages
and aircraft types	climate impacts for costs (leakage)
A better score can be rewarded by lower levies and charges	

5.2.3 References

[i] Sustainable Aviation, "Sustainable Aviation Fuels Road-Map", 2020

[ii] Dahlmann, K., Koch, A., Linke, F., Luehrs, B., Grewe, V., Otten, T., Seider, D., Gollnick, V., Schumann, U., "Climate-Compatible Air Transport System-Climate Impact Mitigationn Potential for Actual and Future Aircraft", 2016

6. Conclusion and future work

6.1 Review of deliverable D1.3

Deliverable 1.3 provides a preliminary assessment of 25 different OIs in relation to Climate-optimised operation of the airline network, Climate-optimised trajectory, Operational and infrastructural measures on the ground, and Operational measures at regulatory level. The state-of-the-art in literature has been researched to detail the current understanding of the strategy and the gaps left to be addressed in order to implement the OIs successfully. The findings presented here will be further researched by the partners involved in the following work packages and deliverables.

6.1 Links to work package WP1

Work package 1 consists of five tasks. The present deliverable addresses the third task, T1.3 – Assessment of operational improvement against identified KPIs, combining the output of T1.1 and T1.2. The potential benefits and disadvantages of each of the operational improvements have been described to the best of the current state-of-the-art. As yet, the research has mostly focused on quantitative KPIs, while qualitative Key Performance Areas as the Human Performance of the practitioners involved in the operations at all levels (pilots, controllers, ground staff, etc.) and the Societal Acceptance of the proposed OIs has been considered only speculatively. A more detailed analysis of these aspects, which may have an important role in boosting or abating the potential some of these OIs have to be actually implemented, will eventually be considered in our future work.

The activities of WP1 will continue in the next tasks T1.4 and T1.5. The objective of T1.4 (expected at the end of month 12) is to select operational improvements that provide the best alternatives based on the assessment executed and presented in this deliverable. The selection will be based in terms of climate impact mitigation, while taking into account the non-climate KPIs to account for stakeholders' interests. In month 25, T1.5 will complete providing a detailed analysis of the operational improvements selected in T1.4. Based on the feedback from different stakeholders and the knowledge gained in WP2 and WP3, the second round of identification, assessment and selection of potential improvements will be executed in T1.5, to identify further possible improvements for analysis in WP2 and WP3.

References

[1] D. S. Lee *et al.*, "Transport impacts on atmosphere and climate: Aviation," *Atmos. Environ.*, vol. 44, no. 37, pp. 4678–4734, 2010.

[2] EUROCONTROL, "COVID-19 impact on the European air traffic network." [Online]. Available: https://www.eurocontrol.int/covid19. [Accessed: 22-Jul-2020].

[3] ATAG, "Climate change." [Online]. Available: https://www.atag.org/our-activities/climate-change.html. [Accessed: 29-Apr-2020].

[4] ClimOp Consortium, "D1.1. Definition of climate and performance metrics," 2020.

[5] ClimOp Consortium, "D1.2 – Inventory of operational improvement options," 2020.