CLIMOP

Climate assessment of innovative mitigation strategies towards operational improvements in aviation

D1.2 – Inventory of operational improvement options

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CLIMOP Consortium

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Executive summary

The goal of the ClimOp project is to develop a set of recommendations for regulations and policies for the aviation sector and define mitigation strategies that aim at encouraging state-of-the-art and innovative operational improvements to reduce the climate impact of aviation.

One of the main objectives of the Work Package 1 (WP1) is to identify and rank operational improvements that result in climate impact mitigation while balancing the interests of all stakeholders involved. Deliverable D1.2 addresses the second task of the WP1, which has the purpose of determining the operational improvements with a high potential for significantly reducing the impact of aviation on the climate in terms of CO_2 and non-CO_2 emissions.

Each of the Project partners brought a specific contribution to the deliverable, reporting on and thoroughly analysing, according to their skills and expertise, those operational improvements which have already been explored in a multitude of European and international research efforts. A preliminary and exhaustive inventory of operational improvements is presented in the Table 1 of the present deliverable. The operational improvement are classified in four general categories:

1. Operational and infrastructural measures in flight
2. Operational measures on the ground
3. infrastructural measures on the ground
4. Operational measures at regulatory level

The maturity of these operational improvements greatly vary from measures that are currently being implemented in different sectors of the aviation domain to very ambitious ideas that will need years and perhaps decades to be tested, validated, and implemented.

This deliverable, together with Deliverable D1.1 that defines nine different stakeholders and categorizes 47 KPIs into five groups (environmental, technical, operational, safety, and economical), constitutes a preliminary assessment which will be used to build an initial block of the most promising improvements. These will be progressively refined for a more detailed analysis on their climate impact mitigation potential within WP2. If their potential is confirmed, strategies leading towards their implementation will be developed and assessed by different stakeholders in the context of WP3.

1. Introduction

Aviation emissions of carbon dioxide (CO_2), water vapour (H_2O), nitrogen oxides (NO_X), sulphur oxides (SO_X), soot and sulphate aerosols alter the concentration of atmospheric greenhouse gases and trigger the formation of persistent contrails and cirrus clouds in ice-supersaturated regions. The share of aviation amongst all anthropogenic CO_2 emissions is about 2% [1], while the contribution of aviation to the total anthropogenic radiative forcing (RF)[1] reaches approximately 5% when non-CO_2 emissions are taken into account [2]. If no actions are undertaken, the adverse impact of aviation on environment and climate will significantly grow over the next decades with the projected increase in air traffic by 3-4% per year. For this reason, international organisations such as the International Civil Aviation Organization (ICAO), IATA, the Air Transport Action Group (ATAG), the European Aviation Safety Agency (EASA), Airports Council International (ACI), and the European Commission have urged the Aviation industry to identify and implement mitigation strategies to reduce the impact of aviation on the environment and climate [3]. As a consequence, global associations of the aviation industry, under the coordination of ATAG, committed to a set of ambitious high-level climate action goals [3]:

- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020.
- A cap on net aviation CO_2 emissions from 2020 (carbon-neutral growth).
- A reduction in net aviation CO_2 emissions of 50% by 2050, relative to 2005 levels.

To meet these goals, the aviation industry has set up a strategy based on four pillars:

1. The development of new technologies, including environmentally friendly aircraft technologies and sustainable aviation fuels.
2. Establishing more efficient aircraft operations.
3. Improving the infrastructure, including modernised air-traffic-management systems.
4. Establishing a single Global Market-Based Measure to fill the remaining emissions gap.

In line with this strategy, public and private organisations in Europe have put powerful efforts to reach the goal of a climate-sustainable aviation within the next decades.

1.1 Development of a "sustainable aviation roadmap for Europe"

In the framework of the Clean Sky and Clean Sky 2 programmes, aircraft manufacturers have been working on environmentally-friendly aircraft technologies in Europe (cf. Pillar 1 above). The harmonization of the European ATM system is being promoted by the SESAR and SESAR2020 programmes (Pillar 3). Moreover, in 2016 ICAO agreed on a Resolution for a global market-based measure to address CO_2 emissions from international aviation (Pillar 4), which paved the way for the so-called Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA aims to stabilise CO_2 emissions at 2020 levels by requiring airlines to offset the growth of their emissions from 2021 (carbon-neutral growth).

Specific actions have been identified and carried out to foster a climate-friendly growth of the aviation industry also at airport level. These actions and their long-term objectives have recently been agreed upon at international level.

A4E Aviation Summit

The objectives discussed on 3rd March 2020, in Brussels, during the 4th Annual A4E Aviation Summit, mostly meet those under the scope of the ClimOP project. In A4E, airline representatives and global aviation leaders have joined forces with Europe's airports, manufacturers and air navigation service providers with the specific target of developing a cross-sectoral climate initiative.

[1] IPCC defines Radiative Forcing as *"a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and as an index of the importance of the factor as a potential climate-change mechanism."* (IPCC AR4)

The study of a “sustainable aviation roadmap for Europe” will identify opportunities for necessary decarbonisation actions, either through technology, operations, sustainable aviation fuels or price incentives.
To address the industry’s sustainability challenge, a basket of measures have been identified in four key areas:

- Efficiency of the air traffic management through the further implementation of Single European Sky (SES), which could reduce CO_2 emissions by up to 10%, resulting in 25 million tonnes of emissions savings per year, and the update of the SES regulatory framework by 2021 [4], [5];
- Dedicated EU industrial policy for the development and uptake of Sustainable Aviation Fuels (SAFs), which could reduce CO_2 emissions from aviation by up to 85%;
- Stepped up global climate diplomacy efforts and full implementation of the UN’s international aviation climate protection system, CORSIA[2];
- Investments and incentives for innovations such as electric and hybrid engine technologies, which would help airlines move away from fossil fuels.

In order to manage traffic safely and efficiently into and out of busy airspace, ANSPs apply airspace restrictions to maximise capacity, reduce complexity and organise aircraft into specific flows. These restrictions may however contribute to reducing horizontal and/or vertical flight efficiency.
In current low-level traffic scenario (e.g. COVID 19), most of these airspace restrictions must be lifted, which enables more direct routes and allows aircraft to fly their optimal vertical profiles. In this situation there will be no reason why an aircraft should not be flying its ‘perfect planned flight´ anymore!

European Aviation Environmental Report 2019
The European Aviation Environmental Report 2019 published by EASA covers, among different topics, the “Environmental Impact Mitigation Measures” [4], describing Airports’ environmental performance improvements in various areas. The overview is based on the 51 airport responses to the ACI EUROPE survey in 2018, which represent 60% of total EU28+EFTA passenger numbers.

1. Vehicle fleet - 86% of the respondents reported that their vehicle fleet included electric vehicles, 47% have hybrid models and 35% have vehicles that run on sustainable alternative fuel.
2. Energy - 61% of survey respondents indicated that renewable energy is produced on site while 40% have established an energy management system certified according to the ISO 50001 standard. In addition, 65% of airports purchase electricity from renewable sources.
3. Airport infrastructure - 82% of respondents provide electricity to aircraft on-stand directly from the local grid through the Fixed Electrical Ground Power (FEGP) and 58% of respondents use the airport’s air conditioning system to provide Pre-Conditioned Air (PCA) to control the temperature on board.
4. Airport surface access – surface access transport (e.g. the road access to the airport) originate most of the indirect emissions at airports. 98% of airports responding to the ACI EUROPE 2018 survey indicated that public transport was available, while a majority of airports also reported that less than 20% of their employees actually use it to travel to work.

These topics, among the many treated in the European Aviation Environmental Report 2019, are well represented in the ClimOP Project.

[2] CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation. Under CORSIA, airlines are required to compensate the increase in CO_2 emissions above 2020 levels covered by the scheme. It is forecast that CORSIA will mitigate over 2.5 billion tonnes of CO_2 between 2020 and 2035. This system will offset growth-related emissions from global air traffic and make international air traffic growth CO_2-neutral.

1.2 The ClimOP project

In the context of the European commitment to research new methods and technologies aimed at reducing the impact of aviation on climate, four projects were selected by the Innovation and Networks Executive Agency (INEA) within the action “Aviation operations impact on climate change”. These four projects are:

1. GreAT (Greener Air-Traffic Operations).
2. ACACIA (Advancing the Science for Aviation and Climate).
3. ALTERNATE (Assessment on alternative aviation fuels development).
4. ClimOP (Climate assessment of Innovative Mitigation strategies towards OPerational improvements in aviation)

The four projects contribute to the general objective by focusing on complementary aspects. In particular, GreAT investigates new concepts to manage air traffic in a climate-friendly way, e.g. by using Trajectory Based Operations (TBO) and adapted airspace design, ACACIA’s objective is to improve the scientific understanding of the contribution of aviation to climate change, while the exploration of new aviation fuels considering technical, economical, and environmental aspects is pursued by ALTERNATE. The focus of ClimOP is the identification of the operational improvements (hereinafter OIs) that, if introduced in aviation operations, have the potential to produce an overall positive impact on climate.

More in detail, ClimOP specific objectives are:

1. to determine alternative most-promising sets of compatible state-of-the-art and innovative OIs to reduce climate impact taking CO_2 and non-CO_2 effects into account,
2. to quantify the climate impact of the alternative sets of OIs determined in Objective 1,
3. to evaluate the stakeholder impact of the alternative sets of OIs determined in Objective 1,
4. to develop a body of harmonised mitigation strategies for each alternative set of OIs determined in Objective 1,
5. to provide recommendations for target stakeholders on policy actions and supporting measures to implement the alternative sets of OIs.

The ClimOp consortium is adopting the following six-step strategy (summarised in Figure 1) to reach its objectives:

- To identify all stakeholders that are potentially involved in the implementation of OIs in the aviation industry (airlines, airports, ANSPs, manufacturers, passengers, etc.) and their needs.
- To define a list of impact indicators and a methodology which will be adopted to quantify the impact of the OI sets on climate and on each of the Aviation stakeholders.
- To compile a list of the OIs that are currently being considered and discussed, specify a realistic time horizon on which these improvements can be implemented in day-to-day aviation operations, and identify the most promising sets of compatible OIs that, when introduced, reinforce each other’s positive climate impact.
- By adopting appropriate modelling tools, to quantify the climate impact and the economic impact on the aviation stakeholders of alternative sets of OIs.
- To develop harmonised mitigation strategies for the alternative sets of OIs and define the methodology to validate such strategies
- To identify influencing target stakeholders, both from aviation and from the political and economic framework, specify their needs and interests, and derive recommendations (in terms of policy actions and supporting measures) for them to ease the implementation of the selected mitigation strategies.

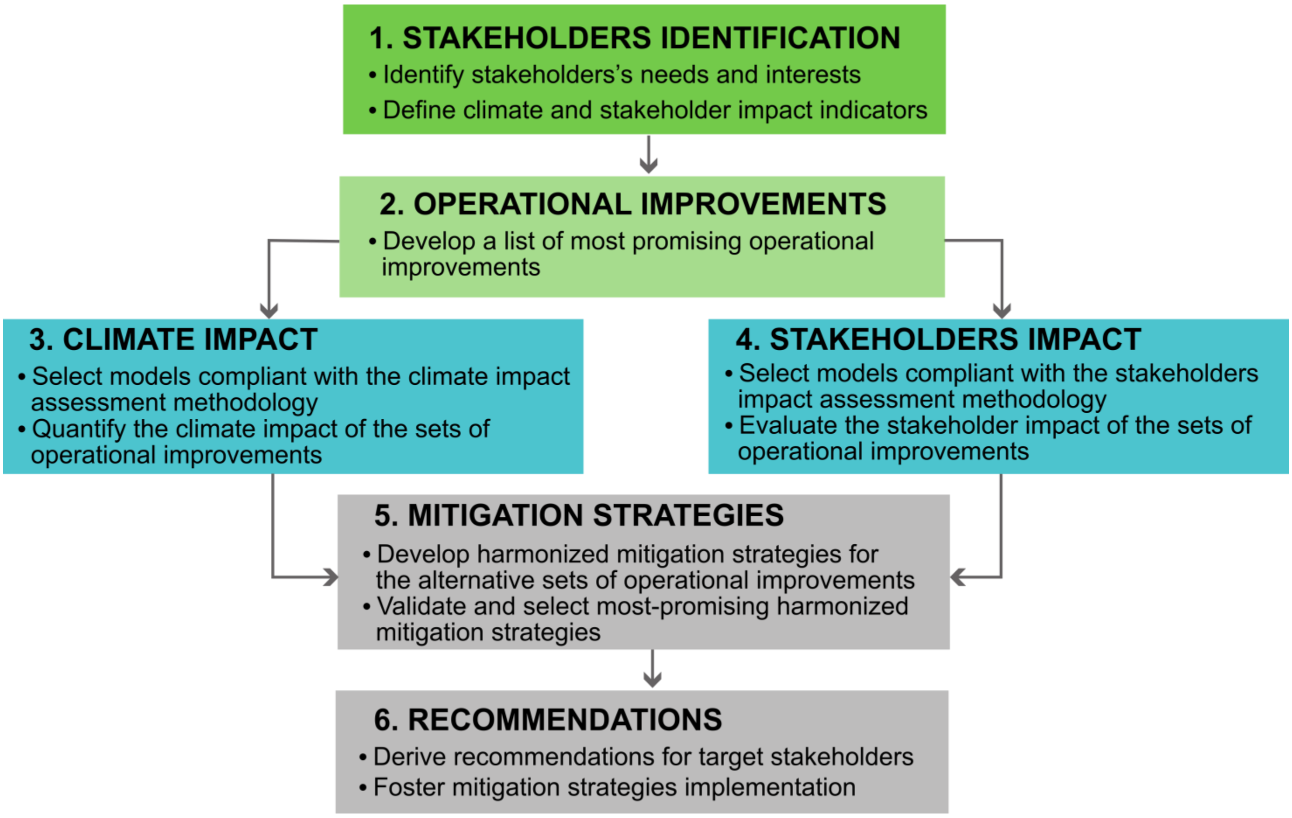

Figure 1. ClimOP six-step strategy to reduce the impact of aviation on the climate

1.3 Work package 1

The activities of the first Work package (WP1) consist of the identification of a carefully-reasoned list of OIs that result in a climate impact mitigation. In this process, the interests of all the involved stakeholders are taken into account and balanced, to ensure that the proposed OIs are feasible to implement and the stakeholders are engaged and motivated to pursue the overall goal of reducing the climate impact of aviation.

The first step of this process is to define a list of all possible OIs which have the potential to yield a positive mitigation effect on the aviation impact on climate. To assess the impact and feasibility of each OI and rank them to identify the most-promising ones, a set of Key Performance Indicators (KPIs) will be defined. The complete list of KPIs currently taken into consideration is described in detail in Deliverable 1.1 [6]. These KPIs include both climate impact metrics and metrics representing stakeholders' needs and priorities, to ensure a balanced assessment which also accounts for requirements such as operation safety, practical feasibility, and long-term economical sustainability.

The quantitative assessment of the proposed OIs for each of the KPIs will be carried out iteratively. After a preliminary, qualitative assessment, the most promising improvements will be selected for a more detailed analysis, which will quantify their climate impact mitigation potential (in WP2). If their potential is confirmed, the analysis will continue with the elaboration of strategies leading towards their implementation by different stakeholders (in WP3). The detailed analyses in WP2 and WP3 will allow to quantitatively assess the OIs identified in WP1 and discard those with insufficient climate-impact mitigation potential, that are infeasible or not viable for various reasons, e.g. safety or reliability.

The feedback from WP2 and WP3 will be used to revise the complete list of OIs and eventually identify additional OIs in a second round of assessment. As a result of this iterative process, the outcome of WP1 will be a set, or a compilation of alternative sets, of feasible OIs with the highest potential to reduce the impact of aviation on climate and thus minimise aviation's contribution to climate change.

1.4 Deliverable 1.2 in the Project's context

The objective of the present deliverable D1.2 is to identify operational improvements that have the potential to significantly reduce the contribution of aviation to the global anthropogenic CO_2 and non-CO_2 emissions. This deliverable targets the OIs that are currently being deployed or about to be deployed and those that are currently being explored. The comprehensive list of OIs identified and discussed within the ClimOP consortium will be presented and described in the next session. As discussed in Sect. 1.3, the results of D1.2 constitute the starting point of the ClimOP assessment analysis of the proposed OIs. The complementary step in this analysis is the definition of KPIs to evaluate the impact of such OIs on the climate and on the aviation stakeholders. The identified KPIs are described and discussed in the Deliverable D1.1 - Definition of climate and performance metrics [6]. As a consequence, D1.1 and D1.2 lay the foundations of the iterative OI selection process which will converge, in the course of the project, in a progressively refined list of alternative sets of OIs.

2. Inventory of operational improvement options

The partners of ClimOP, according to their activities and expertise, compiled a preliminary inventory of Operational Improvements (OIs) which exhibit a potential to reduce the overall impact of the aviation industry on climate. A comprehensive list of all identified OIs is presented in Sect. 2.1. The subsequent Section 3 describes the identified OIs and organise them in broad categories according to the sector of operations they impact, for example the Airline network (Sect. 3.1), the trajectories (Sect. 3.2), the ground operations (Sect. 3.3), and the regulatory level (Sect. 3.4).

2.1 Table of all identified Operational Improvements

Table 1 presents all identified OIs, the benefit they are expected to bring in reducing the impact on climate, the necessary requirements and challenges to be overcome to implement the operation changes, and the stakeholders involved. Table 1 summarises the preliminary inputs from the all members of the project team. These OIs will be further discussed and refined over the course of the project and evolve into a final, well-reasoned list that will be reported in deliverable D1.5 "Report on the second iteration for the identification, assessment and selection of operational improvements". In Sections 3 and 4, a selection of the OIs presented in Table 1 are described in some detail.

Table 1. Preliminary list of all OIs identified by the ClimOP Consortium

Concept	Benefits	Challenges	Requirements	Stake-holders	References
Operational and infrastructural measures in flight					
Climate-optimised Intermediate Stop Operations (ISO)	– Reduced fuel consumption up to 16% – Reduced CO_2 and non-CO_2 emissions	– Detours – Increased flight times – Increased numbers of departures/arrivals – Local impact near airports – Airport capacity availability – Passenger acceptance	– Aircraft redesign for shorter ranges for additional savings – Non-CO_2 induced RF should not be greater than CO_2 induced RF saved	Airlines Passengers Airports ATM; ATCo's	WeCare project [7]; [8]–[12]; DSE report (2009)
Formation Flying	– Reduced fuel consumption and emissions – Extended range	– Synchronized flight plan – Rendezvous manoeuvre – Passenger comfort and acceptance – Pre-formation merging/splitting/ detouring – Safety/separation	– Planning process and benefit sharing agreement – Airspace infrastructure	Airlines Passengers Airports ATM ANSPs IATA, ICAO	LuFo project FORMIC; Marks et al. (2020)
Satellite-based navigation/ guidance for descent	– Fuel & CO_2 saving – Time saving – Noise reduction	– Possible conflicts between local ANSPs needs and the guidance system – Network of satellites dynamically linked to ensure continuous coverage with low latency	Area navigation (RNAV), Required Navigation Performance (RNP)	ANSP, Airports, Airlines	[13] pp. 64, 68
Wind/weather -optimal dynamical flight planning	– Optimised flight altitude/ trajectory according to wind/ weather data – Avoid last-minute re-routing – Reduced fuel consumption and emissions – Reduced flight time	Frequently updated and reliable large-scale wind forecast/data	– Consideration of flight time as one criterion within integrated multi-criteria flight planning process (e.g. optimizing for min. en-route nav. charges may lead to different route) – Flight simulation – Flight-weather dependency simulation	Airlines; ANSPs	Common NASA/DLR activity, [13] pp. 60, 77, [14], [15]

Concept	Benefits	Challenges	Requirements	Stake-holders	References
Climate-optimized flight planning	Reduced climate impact	– Tendency to fly lower and in narrow altitude band causes challenges to ATM – Climate impact reduction needs to be balanced with additional fuel burn/flight-time/costs at non-optimal altitude and in order to deliver viable routes – Prediction of strength and accurate localisation of non-CO_2 climate effects – Implementation of CCFs in the weather model and in the overall trajectory optimisation (SWIM) – Calculation of an equivalent CO_2 effect for the non-CO_2 species – Economic measures to support climate optimised routings	– Supercomputing – Consideration of climate impact as one criterion within integrated multi-criteria flight planning process	Airlines, ANSP/ATM ICAO, IATA, Aircraft trajectory planners	EU projects REACT4C, ATM4E; [16], [17]
Climate optimised North-Atlantic Track System	Reduced climate impact	– Prediction of non-CO_2 climate effects – Calculation of an equivalent CO_2 effect for the non-CO_2 species	Supercomputing	ICAO, IATA, Aircraft trajectory planners	This report
Climate-restricted airspace	Reduced climate impact by reducing the emissions in more climate-sensitive regions	– Accurate localisation of non-CO_2 climate effects – Detouring, – Non-optimal flight altitude – Increased flight times –	– Flight planning tool – Need for a regular update of restricted airspaces (e.g. based on daily weather, publication through AIS channels)	Airlines ANSP/ATM	[7]; [18]
Climate-charged airspaces	– Reduced climate impact – Reduced DOC	– Accurate localisation of non-CO_2 climate effects – Detours, Increased flight times – Passenger acceptance	– Flight planning tool – Need for a regular calculation of unit charges for airspaces (e.g. based on daily weather, publication through AIS channels)	Airlines ANSP/ATM	DLR project Eco2Fly, [19]

Concept	Benefits	Challenges	Requirements	Stake-holders	References
Flying low and slow	Reduced climate impact for comparably low additional costs	– Increased flight times – Increased fuel consumption – Increased DOC – Airspace capacity availability – Prediction of non-CO_2 climate effects – Calculation of an equivalent CO_2 effect for the non-CO_2 species – Economic measures to support lower and slower flight	Aircraft redesign for new design parameters to gain additional potential	Airlines, Passengers OEM, ICAO, LH, Aircraft trajectory planners	DLR project CATS; [20], [21], [22]
Free routing in high-complexity environment/ flexible waypoints	Reduce distance flown through optimal routing	– Safety – Timely availability of weather/climate change info	– Non-CO_2 induced RF should not be greater than CO_2 induced RF saved – Airspace infrastructure	ANSPs; Airlines; ATM; ATCo's	[23], [13] p. 72
Multi-sector/ sectorless planning	Reduce fuel consumption due to reduction of constraints at sector boundaries	– Safety – Coordination across sectors – Requires new role(s)	Redesign of airspace management and infrastructure	ANSPs, Airlines, ICAO	[24]
ANSP collaboration across oceanic airspace	– Flight level optimization – Safety	– Coordination across sectors	Satellite datalink	ANSPs, Airlines, ICAO	[13] p. 62; [15]
Optimized long-haul flights	Fuel & CO_2 saving	– Coordination across sectors – Feasibility in congested airspace	Cooperation of aviation authorities of multiple countries	ANSP, Airlines	[13] p. 63, [25]
Routing optimised for contrail (night) avoidance	Reduction of warming caused by contrails	– Prediction of climate effects of contrails – Implementation of contrail formation in the weather model – Calculation of an equivalent CO_2 effect for contrails – Economic measures	Supercomputing	ICAO, IATA, Aircraft trajectory planners	[26]

Concept	Benefits	Challenges	Requirements	Stake-holders	References
Early morning arrival optimization	– Fuel & CO_2 saving – Time saving – Noise reduction	– Feasibility in congested airspace – Coordination between Airlines, ANSPs and airports	Flight planning	ANSP, Airports, Airlines	[13] p. 65, [27]
PBN for landing	– Fuel & CO_2 saving – Time saving – Noise reduction	– Feasibility	Performance-Based Navigation (PBN)	ANSP, Airports, Airlines	[13] pp. 66-67 [28]
Continuous Climb/De-scent Operations	– Reduces fuel consumption – Aircraft noise – Emissions	– Integration to the current system – Requires training – Operational drawbacks	Training	ANSPs, Airlines, Airports	[29]; [13] pp. 70-71
Departure/ Arrival Management extended to en-route Airspace (DMAN, AMAN)	– Less fuel burn from reduced vectoring at lower levels – Reduced holding and maintaining more fuel-efficient flight levels for longer	– Cross-border coordination – Overlap between queue management processes and Air Traffic Flow Control Management	Collaborative decision making processes	Airports, Airlines	[30] pp.54, 60
Time-Based Separation for Final Approach	– Reduction holding times – Less fuel burn	– Safety	– New wake-vortex separation standards – Training Air Traffic Controllers	Airports, Airlines, ANSPs	[30] p.60, SJU Solution #64, [31]
Optimal separation minima	– Less detouring – Shorter flight times – Reduced fuel consumption and emissions	– Increased ATC workload – Safety	- ATC infrastructure - Wake vortex re-categorisation	Airlines; ANSPs	[32], [33]
Reduced wake vortex separation standards	– Increase airspace and Airport capacity – Reduce queuing time	– Safety	- Real-time wake vortex measurement	ANSP, Airports, Airlines	[13] p. 69

Concept	Benefits	Challenges	Requirements	Stake-holders	References
Move merge points closer to airport	– Fuel & CO_2 saving – Avoid noise-sensitive areas	– Coordination between queue management processes and Air Traffic Flow Control Management	– PBN	ANSP, Airports, Airlines	[13] p. 61
Strategic planning: merge/separate flights; optimal hub-spokes/point-to-point operations	Route optimal network	– Cooperation between competing airlines – Maintaining network quality – Fleet adaptation	– Airport infrastructure – Slot management (grandfather rights)	Airlines, Airports, Pax, ATM	This report
Enhanced User-Driven Prioritisation Process (UDPP)	– Less Delays – Better use of Capacity Airspace	Inter change of Information (SWIM)	– Collaborative Decision Making	ANSP, Airports, Airlines	SJU Solution #57 [34]
Operational measures on the ground					
Increased runway and airport throughput	– Enhance airport runway throughput due to separation reduction – Wake separation reduction – Single and multiple runway optimisation – Separation reduction using advanced satellite systems – Maximise runway occupancy	– Safety	– Optimised wake turbulence separation minima and separation delivery – Optimised runway delivery	ANSPs, Airlines, Airports	SESAR PJ.02 [35]
Minimize Airport queueing time	Optimized taxi route network	– Planning – Delay minimization – Gate assignment and occupation – Runway allocation	Make sure to hold freed slots	Airlines, Airports, ATM	[13], [36]

Concept	Benefits	Challenges	Requirements	Stake-holders	References
Airport Collaborative Decision Making (A-CDM)	Reduction of taxi time	Coordinated operations among airline ramp operators, central airline control, Port authority, departure and arrival manager	Hardware and software technology for prompt information exchange and decision ranking	Airports, Airlines, ATC	[30] p.54, 59 [13] p. 17
Optimize gate departure for runway slot	Avoid burning fuel in departure queue	Coordination between ramp control, aircraft and ATC	Collaborative Decision Making	ANSP, Airports, Airlines	[13] p. 86
E-taxi (tow truck)	Less emission near ground	– Longer operating times of trucks – Additional roads for trucks driving back to gates – Investments in more trucks – Commonality and logistics (timely available; match aircraft size) – Need for business case	– Climate friendly energy sources	Airports (ground movements); ground services; infrastructure; interactions with flow-management	[37]
E-taxi (tug wheel)	Less emission near ground	– Increased operation weight – Increased fuel burn in the air – Increased emissions in the air – Need for business case	– Business sustainability assessment – Climate friendly energy sources	OEM; Airlines; Airports (ground movements)	[38]
E-taxi Hybrid	Less emission near ground	– Both aircraft and airport need to be equipped / modified – Connection between systems needed – Need for business case	– Climate friendly energy sources	OEM, Airports, Airlines	[13]
Single engine taxiing	– Fuel & CO_2 saving – Noise reduction – Pollutant emissions reduction	– Low grip conditions – Engine start-up and cooling	– Airlines procedural change	Airlines	[13] p. 87

Concept	Benefits	Challenges	Requirements	Stake-holders	References
Flexible runway usage	Shorter flight routes between airports under mild wind conditions	– Air traffic control – Complexity – Safety – Trade-off between capacity and demand – Increased noise in sensitive areas	Automated and near deterministic flight scheduling	ANSP, Airlines, Airports	[25]
Parafoil landing	– Reduces aircraft noise – Reduces emissions	– Requires a new design by manufacturers Operational drawbacks	– New aircraft design	Aircraft Manufacturers, Airports	[39]
Magnetic Levitation for take-off and landing	Reduces: – fuel consumption – aircraft noise – emissions weight (undercarriage system can be ignored)	Requires major operational, infrastructural, and design changes	– New design – Operational changes	Aircraft Manufacturers, Airports	[39]
		Infrastructural measures on the ground			
Fixed Electrical Ground Power (FEGP) and Pre-Conditioned Air (PCA) to aircraft at the airport gate	– Reduce fuel burn & CO_2 emissions, noise and pollution – Avoid use of Aircraft Auxiliary Power Unit (except for engine start) – Pilot obtains electricity from local grid and uses airport's air conditioning system to control temperature on board	– Return on investment – Feasibility in large/ high-traffic airports – Depend on ground staff to connect aircraft to power/air	– Hardware installation at as many gates/stands as possible	Airports Airlines	[30] p.68 [13] p. 82
Renewable energy produced at airport	– Significant reduction of emissions – Reputational gains	– Budgeting – Design – Authorization process – Installation – Maintenance (staff training)	– Purchase or self-production of electricity from renewable sources – Feasibility study	Airports	[30] p.67 p.71 SEA - Environment and Airport Safety Dept.

Concept	Benefits	Challenges	Requirements	Stake-holders	References
Improved ground transport access	– Reduced emissions around airports/cities – Reduction of the number of individual vehicles transporting passengers and airport operators to the airport – Reputational gains	– Economic measures to support local communities – Budgeting – Change of mentality	– Availability of charging stations and electric vehicles (agreement with third party suppliers) – State / regional incentives for the purchase of electric cars	Airports, Administrative entities, Suppliers	[30] p.68 SEA - Environment and Airport Safety Dept.
Implementation of a monitoring system for the atmospheric emissions	– Continuous and precise monitoring of emissions for future targeted improvements – Reputational gains	– Budgeting – Design – Authorization process – Installation – Maintenance (staff training)	Choice of the detection system according to the parameters to be monitored: CO_2 NOx, PM10, etc	Airports, Administrative entities, Municipalities	SEA - Environment and Airport Safety Dept.
Upgrade of the existing infrastructure according to energy efficiency criteria for the reduction of environmental impacts	– Reduction of energy consumption – Reputational gains	– Budgeting – Search for new materials / training – Authorization process	– Authorization permits (ENAC approval) – Feasibility study	Airports, Administrative entities, Municipalities	SEA - Environment and Airport Safety Dept.
Voluntary initiatives to reduce CO_2 emissions	– Reduction of emissions until reaching 0-emissions by 2050 – Reputational gains	– Budgeting of the change of power sources and technologies (e.g.: hydrogen) – Change of mentality – Staff training	– Purchase or self-production of electricity from renewable sources – Training	Airports	SEA - Environment and Airport Safety Dept
Operational measures at regulatory level					
Limit "climate unfriendly" aircraft operations	Reduced CO_2 and non-CO_2 emissions	– Variable impacts per region – Fleet adaptation – Distorted competition	Encourage airlines to prefer reduced climate impacts over costs	Airlines, States, ATM	This report

Concept	Benefits	Challenges	Requirements	Stake-holders	References
Trade flight frequency for aircraft size	Less flights with potential emissions reductions	– Merge networks and operators – Optimise load factors – Minimize pax transit time	Make sure to hold freed slots	Airlines, Airports, Pax	This report
Environmen-tal scoring	Flight characteristics based operating restrictions	Variable impacts per region and operation	Ensure that airlines do not trade climate impacts for costs (leakage)	Airlines, States, ATM, Airports	[13]

3. Selected Operational Improvements

A sample of the OIs presented in Table 1 is thoroughly described in the following, according to the criteria discussed in Section 4. These selection aims at giving an overview of the different categories of measures that are currently analysed in the literature on the aviation domain, and of the very different levels of maturity, feasibility, and timescales for implementation of the proposed OIs.

3.1 Climate-optimised operation of the Airline network - Operational measures in flight

3.1.1 Climate optimised intermediate stop- over[3]

It can be shown with aircraft design relationships that the fuel efficiency for the transport of a given payload decreases with increasing design range under the same assumptions and with the same technology level. The reason for this is that airplanes with a longer range require larger tank capacities, which are reflected in the dimensioning in an increased structural weight (enlarged wings, reinforced wing root). For each additional kilogram in the operational empty weight (OEW), additional 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. Green and collaborators use the ratio of payload to the product of range and fuel consumption, which is also referred to as the referred to as the payload range efficiency (PRE) [40].

Figure 2 shows the PRE as a function of the flight distance of an aircraft designed for 15,000 km range. The design point A indicates the maximum payload at MTOW, and the design point D shows the reduced payload but maximum seat load factor. It can be seen that, for such a long-haul aircraft, the maximum payload range efficiency, depending on the design point, is achieved at route lengths between 4000 and 6000 km, which is well below its design range. The dashed lines also show the envelope of the design points for a variation of the design range for new aircraft. Accordingly, the PRE can be significantly increased by reducing this design range.

3 This summary is largely based on a comprehensive literature review provided by Linke (2016) [78].

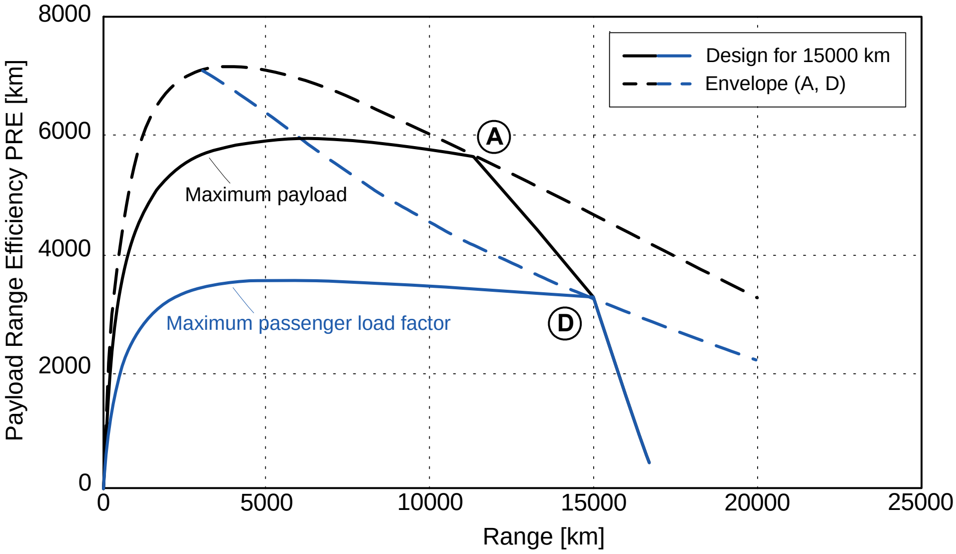

Figure 2. Payload-Range-Efficiency as a function of flight distance. Point A: maximum range with maximum payload and MTOW. Point D: Design point for reduced payload with maximum seat load factor (Figure adapted from [41]**).**

For example, aircraft with a range of less than 6000 km provide their maximum fuel efficiency approximately at their design range, so that an aircraft designed for 6000 km has about twice the PRE as a long-range aircraft designed for 15 000 km on a 6000 km long mission.
The use of aircraft with a shorter range and refueling, e.g. during stopovers on long routes, can therefore save considerable fuel for the reasons set out. This can also result in a reduction in the pollutants arising in flight and a reduction in direct operating costs. However, fuel savings can also be achieved with existing long-haul aircraft if a stopover is made to refuel the aircraft. The theoretically achievable fuel savings increase with increasing mission length, so that Intermediate Stop Operations (ISO) is particularly interesting for long-range missions.

Previous research

As part of a parameter study, Green [42] demonstrated the dependency of the payload range efficiency of PRE kerosene-powered aircraft on mission length and design range with a simplified Breguet formula-based approach and thus clarified the fuel efficiency advantages of medium-range models. According to that, an aircraft designed for 6000 km would have a 41% higher PRE on a 6000 km mission than an aircraft designed for 15 000 km on the same mission. Based on these findings, the possibility of using aircraft with a shortened design range for the operation of long-haul flights, and refueling them in between was discussed for the first time. The concept of multi-stage long-haul operations was particularly suggested in the study by Green, in which refueling is carried out by making stopovers at suitable airports. Taking into account the fact that possible intermediate airports are not optimally located in terms of geography, the study also made a first estimate of the so-called sec θ effect based on trigonometric relationships on the maximum permissible detours. The sec θ effect can be used to estimate the maximum permissible course deviations from the direct flight connection for a given maximum detour.
Since then, numerous studies have been devoted to the topic of ISO, with different approaches used to quantify the potential of the concept. In addition to analytical methods for estimating the weight breakdown of aircraft designed for shorter ranges based on the Breguet range formula, preliminary aircraft design methods based on standard handbook procedures as well as higher fidelity design tools were applied. The analysis scope ranges from generic individual missions to fleet or global level analyses, while both optimally located intermediate airports and real geographical airport distributions and route structures were assumed. In addition to the fuel savings that can be achieved with the concept, the implications on flight times, operating costs, life cycle costs, environmental impact and safety were also analyzed. Also, studies on the suitability of

airports for ISO based on their geographic location were carried out and the number of additional flight movements was assessed. In addition to the positive implications of the “Intermediate Stop Operations” concept on fuel consumption and operating costs, many authors deduced that the concept has the potential to reduce the environmental impact of air traffic. With regard to CO_2 characteristics, this conclusion is valid, but in order to make a statement about the influence of the concept on non-CO_2 emission distributions and their climate impact, a more detailed consideration of the changes in quantities and distributions of individual pollutant species is necessary.

ISO with redesigned (optimized) aircraft

Most studies so far have focused on ISO with aircraft designed for shorter ranges as this may release the full fuel saving potential of the concept. Those include the early studies by Green (2006) [41] and Nangia (2006) [43] which found fuel reduction potentials of up to 51% for ISO with two stopovers and idealized mission level assumptions with an aircraft designed for a shorter range. In studies by Poll (2011) [44] and Hahn (2007) [45] these potentials were corrected down to 28-29%. The reason for this reduction is the correction of assumptions with regard to the seating density, which were necessary due to the use of handbook methods for dimensioning the new designs. For ISO with only one stopover, numerous studies indicate savings of between 13% and 23% depending on the design ranges of the new aircraft considered. The achievable fuel savings at fleet or global level were quantified by Green (2005) [40], Langhans et al. (2010) [46], Linke et al. (2011) [47] and Poll (2011) [44]. While Green estimates the potential for ISO with aircraft optimized for reduced range to be about 10%, Langhans et al. and Linke et al. found 10 - 11% as maximum possible savings by performing detailed studies taking into account a real geographical airport distribution for routes served by Boeing 777 and Airbus A330. Poll estimated the globally achievable savings to be 1 - 7% [44]. A first climate impact analysis was presented by Creemers and Slingerland (2007) [48]. They used a simplified method based on generic considerations from the design mission to calculate a 13% reduction in global warming potential, in which the slightly increased altitude of the new design and the impact of CO_2, NO_x and H_2O emissions of one kilogram fuel as a function of the flight altitude were taken into account.

ISO with existing aircraft

However, also without making changes to the aircraft design e.g. through the introduction of a new medium-haul aircraft, in the short-term aircraft operators may save fuel by using their existing fleet and performing stop-overs on long-haul missions. The possible savings from ISO with an existing aircraft for one stopover were investigated by several authors and are of the order of 5 - 15% depending on the aircraft type used [11], [44], [46], [48], [49]. Poll in particular emphasizes that the gain from one additional stopover is small (approx. 1.8% with an existing aircraft) and therefore, due to further operational aspects, an additional economic benefit compared to ISO operation with only one stopover is hardly to be expected. Linke et al. conducted an extensive system-wide study to determine the implications of ISO with existing aircraft on gaseous emissions and climate. Therein, a realistic air traffic simulation was performed taking into account operational constraints and ambient conditions, like e.g. 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 as well as the impact on climate change was determined by taking into account CO_2 and non-CO_2 effects, arising from contrail-cirrus, water vapour and nitrogen oxide emissions. In agreement with earlier findings it was found 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%. However, due to the nitrogen oxide and water vapour emissions, which are released at higher cruise altitudes and over-compensate reduced warming effects from CO_2 and contrail-cirrus, overall an increased warming effect was found. However, the authors expect a climate impact reduction for ISO even with existing aircraft, avoiding the higher flight altitude in the first flight segment and hence reducing the fuel savings. It is explicitly noted that most likely climate impact benefits could be achieved if lower fuel savings were acceptable. This suggestion, namely the adoption of “Climate-optimized Intermediate Stop Operations”, has to be analyzed in more detail and shall be subject to the ClimOP project.

3.1.2 Optimal hub-and-spoke & point-to-point network

When planning the configuration of the airline network, there are three main strategies: hub-and-spoke, point-to-point, and multi-hub [50]–[52]. 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 [53]. On the other hand, point-to-point strategies allow direct flights between airports, providing high convenience to passengers.

The hub-and-spoke and point-to-point emerge as two competing business models, traditional associated with flag carriers and low-cost carriers (LCC), respectively. On the one hand, 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 [54], [55]. An important 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, LCCs offer a no-frills product to the passengers, opting for a point-to-point network that connects them directly to popular destinations, especially using secondary airports [11].

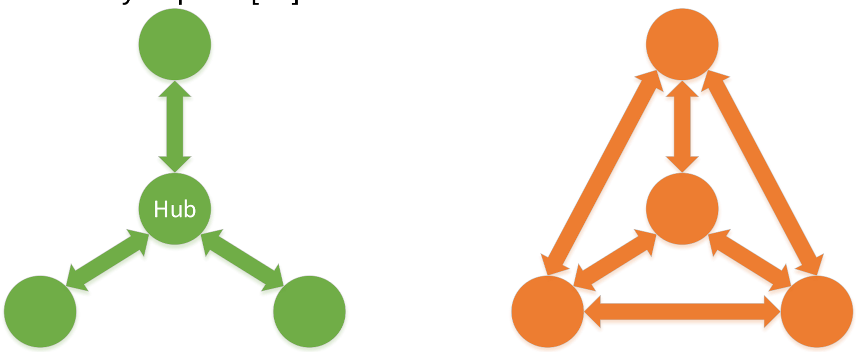

Figure 3. Hub-and-spoke (left) and point-to-point configurations (right, fig. adapted from [49])

Both models, as shown in Figure 3, have inherent advantages and disadvantages. Zgodavová et al. analysed the difference, and created a comprehensive list of pros and cons, many of which are from a passengers’ perspective [11], [52]. As a result, an optimum network will require balancing all these advantages and disadvantages as detailed in Table 2.

An optimal hub-and-spoke & point-to-point network will result in a hybrid system that does not show a traditional network shape. There are two types of spatial indices that Alderighi et al. studied to depict airline network: Gini concentration index, and Freeman network centrality index[49], [51]. Both indexes provide different insights into the structure of the network. On the one hand, the Gini index measures the concentration of frequencies at the main airports. A pure point-to-point network would have all flights distributed equally amongst the airports in the network. Whereas a perfect hub-and-spoke star formation would have a disproportionally higher frequencies on the one or more spokes. On the other hand, the Freeman index measures the morphology or shape by inequality of the network. It is more effective in recognising closeness to classic reference structures of hub-and-spoke and point-to-point. Therefore, creating an optimal network will not only require a balancing act of strengths and weaknesses of classical structures, but it will also need a deeper understanding of spatial morphology of the networks.

Table 2 - Hub-and-spoke versus point-to-point comparison

	Typical Advantages	Typical Disadvantages
Hub-and-spoke	- Cover more city-pair connection with a limited number of routes - Efficient use of resources, particularly labour - Higher frequency of flights - Reduced cost per ASK (CASK)	- Frequent congestions and delays at the hub airport - Low schedule reliability - Overall longer travel times from origin to destination
Point-to-point	- Maximises aircraft utilisation - 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

3.1.3 Splitting long-haul into multiple short-haul flights

Another opportunity of an operational improvement could be a separation of long-haul into several shorter-haul flights. The difference as compared to the ISO concept from chapter 3.1.1 is that the intermediate stop on airports between origin and destination is here not exclusively used for refuelling but realised as a regular stop at a terminal gate that allow passengers to both boarding and deboarding. These processes enable passengers to use the aircraft also for travelling along subsections, which might lead to a better transport performance as possibly unused seats during a nonstop long-haul mission could be sold at least for subsections to passengers whose destination is one of the provided intermediate stop airports.

A network-wide adjustment would establish new hubs and create new interfaces within the global route network and would enhance the passenger's flexibility by having more frequent services and maybe new destinations to reach with only one transfer. From the ATM-system (air traffic management) and the DOC (direct operation costs) perspectives, disadvantages of that concept for some stakeholders could be identified. The network becomes vulnerable to delay as regular intermediate stop services will require further airport capacities. Particularly for some of Europe's big hubs todays airport capacity is close to saturation. Air space sectors in the vicinity of airports might also exceed their capacity, and this would be challenging for the ATC staff (air traffic control). Multi-leg flights with several stops at airports give the passengers the additional opportunity to interchange. However, the actual duration of travel between the initial OD (origin-destination) pair will be extended by several hours, because each intermediate stop requires an entire turnaround cycle. Moreover, the direct operating costs (DOC) of an airline will be affected by both the enhanced costs for the crew and the budget for additional landing, including airport fees and maintenance sessions of both the engine and airframe, due to increased wear caused by more frequent landing and take-off operations. A positive aspect is that the crew changes for different subsections might reduce the jet lag effects.

A drawback of ISO for passengers is that connections often take place in the middle of the night. Experience (e.g. from the Gulf hubs) suggests that this inconvenience is accepted by passengers if fares are comparably low.

Another consequence is that future aircraft models could be redesigned towards shorter ranges. This will result in a reduction of the fuel tank capacity and, in some cases, of the number of engines. Both these design changes directly affect the MTOW (maximum take-off weight), and consequently the fuel consumption and the CO_2 emissions.
Depending on the distance of a certain subsection, lower cruise altitudes and cruise speeds may be reached. That could reduce the probability of the formation of contrails depending on the meteorological conditions in the atmosphere, hence resulting in a direct mitigative effect on aviation climate impact.

In summary, separating long-haul flights into several shorter-haul flights has a potential to reduce the emission of greenhouse gases and thus the climate impact. However, for some stakeholders like the airline, the airport, the manufacturer and the passenger, its application might be linked to a higher effort or cost or lower comfort. Therefore, ClimOP should include a cost-benefit analysis of this OI, to quantify the benefits and assessing the required investments.

3.1.4 Low-capacity, high frequency vs. high-capacity, low-frequency flights

The basic idea of this OI is a trade-off between aircraft size and frequency. Prioritising between the two is a multifaceted problem that involves several stakeholders: airlines, aircraft manufacturers (OEMs), passengers and airports. Wei et al. conducted early studies looking into the reasons why the airline industry in the US domestic market favoured more flights over flying larger capacity, and it mainly came down to economics [56], [57].

The size of an aircraft and the frequency of flights are direct contributors to the overall cost of an airline. Although a larger capacity aircraft does provide some opportunities of reducing operating cost, Wei et al. show that these economies of scale do not extend in the short-haul[17]. Introducing a large plane in the short-haul segment results in higher aircraft capital cost, terminal cost, and labour cost due to the bigger crew. Furthermore, the market preference for the short-haul sector is predominately dictated by the technical efficiency of smaller aircraft alone. A further breakdown of fleet used in the global market shows the short-haul is mainly catered by small aeroplanes and long-haul by larger aircraft, though the latter is due to the required range capabilities. Long-haul routes allow airlines to gain higher profit even on lower-demand routes due to the lower cost-per-unit-distance. In the early 1970s, Airbus introduced the A300, a twin-engine aircraft that was meant to bring the high-capacity and passenger comfort of the larger long-haul aircraft of that era. The FAA regulations regarding extended twin-engine operations (ETOPS-60 rating) meant that the A300 operated mainly short- to medium-haul flights. However, in 1977 when A300 was the first twin-engine aircraft to be certified for ETOPS-75 rating, airlines capitalised on the low cost-per-unit-distance by operating the aircraft on longer routes. The airline economics incentivises manufacturers to design their large capacity aircraft for long-haul. Hence, introducing a more efficient large-aircraft specifically designed for short routes can provide the necessary incentive for airlines to rethink their short-haul fleet [54], [58]. This gap in the market is highlighted by Kölker and collaborators, who evaluated the traffic with respect to three categories: passengers, distance, and aircraft [59]. When surveying the global traffic between 2003 and 2012, the largest share of passengers flew in the 401-800km range, adding up to 7.9 million flights on average per year [56]. Introducing an efficient high-capacity aircraft in this segment can dramatically reduce the flight frequency.

While the current trends are clear from an economic perspective, the environmental impact of these preferences need considerations. Givoni et al. directly explored the implications of aircraft size on the environment by comparing popular Airbus A320 with the Boeing 747 [60]. Although the comparison of these aircraft can be considered unfair due to different design goals and technology generation, it enabled the authors to highlight the sensitivity of cost and operations due to aircraft size. The study found three effects to choice of replacing small aircraft with larger ones: higher local air pollution, lower climate change impact, and lower noise pollution [60]. They do note, however, that there are very few flights of Boeing 747 for short distances, and hence suspect that the benefits are underestimated due to a conservative assumption of high environmental impact. Nevertheless, the study also accounted for indirect benefits such as a lower flight frequency would use fewer slots and therefore result in fewer delays on ground with less fuel burn, and less investment from airports to expand runway capacity. Beyond the aircraft size, Grampella et al. considered the combination of aircraft and engine. They found that two aircraft with the same airframe and no redesign that differ by 1% in the age of their engines, has a local pollution and noise impact elasticity of 0,20% and 0.41% with no other change to operations [61] .

The literature on this mitigation strategy consistently shows environmental benefits for shifting towards larger and newer aircraft. However, the economics of such a shift is the most challenging hurdle. Current technology in aircraft design needs to improve to allow airlines to consider large aircraft for short-haul market.

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3.2 Climate optimised trajectory - Operational measures in flight

This section describes operational measures for climate optimized trajectories to be investigated in ClimOp. The current flight trajectories are mainly optimised with respect to operational costs (typically based on time, fuel, and overfly charges). While minimising the fuel usage lowers the amount of CO_2 emissions, this is not enough to mitigate the climate impact of aviation, as more than 50% of aviation's climate impact is caused by non-CO_2 effects from NO_x (on ozone and methane), water vapour and contrails [2]. These non-CO_2 effects depend not only on quantity of emissions but also on altitude, geographical location, time and the background atmosphere, meaning emissions in certainty locations might cause stronger climate impact than the same emissions in other locations. The operational mitigation strategies for aviation climate can be divided into two aspects: 1) on mission level considering detailed weather situations, e.g., avoiding climate sensitive regions; 2) on fleet level for global air traffic scenarios, e.g., flying lower and slower. Measures in this regard will be discussed in section 3.2.1 and 3.2.2, respectively. Whereas, section 3.2.3 discusses dynamical and satellite-based navigation concerning climate optimized flight planning. In addition, the current approach procedure can be potentially re-optimised horizontally and vertically to address emission and noise issues, which will be discussed in section 3.2.4.

3.2.1 Avoiding climate sensitive areas

Aviation has an influence on global warming through both CO_2 and non-CO_2 emissions, e.g., NO_x, water vapour and particulates. The fact that these non-CO_2 effects have strong temporal and spatial dependency indicates that emissions in certainty locations (or time) might cause stronger climate impact than the same emissions in other locations (or time). Regions in which emissions lead to pronounced climate change are defined as climate-sensitive regions. Previous research has shown that changing flight trajectories to avoid climate sensitive regions has the potential to reduce the climate impact of aviation [62]–[64]. In ClimOp, we consider the avoidance of climate sensitive regions from two aspects: 1) climate optimized trajectories considering both CO_2 and non-CO_2 effects, 2) avoiding the formation of warming contrails.

To allow climate-optimized trajectories calculation, the information on climate impacts are required for the current trajectory optimization tool. The European project REACT4C focused on identifying the climate impact information (known as Climate Cost/Change Functions (CCFs)) for representative winter and summer weather situations [64]. CCFs are 5D datasets (longitude, latitude, altitude, time, type of emission), which describe the specific climate impacts, i.e. the anticipated climate change for a local emission, or in other words, the climate change per flown kilometre and per emitted masses of the relevant species. Fig.2 shows an example of ozone CCFs (right of Fig.2) for a winter weather pattern (left of Fig.2) with a strong jet (dark blue) and a high-pressure ridge, which reaches from Africa to the tip of Greenland. In this high-pressure ridge, the ozone CCFs shows a maximum. Details of these CCFs are presented in Grewe et al. (2014) [65]. Based on these CCFs, a case study of a zonal weather pattern in winter shows a large mitigation potential with a reduction of climate impact of around 25% at a cost increase of about 0.5% for trans-Atlantic flights [16].

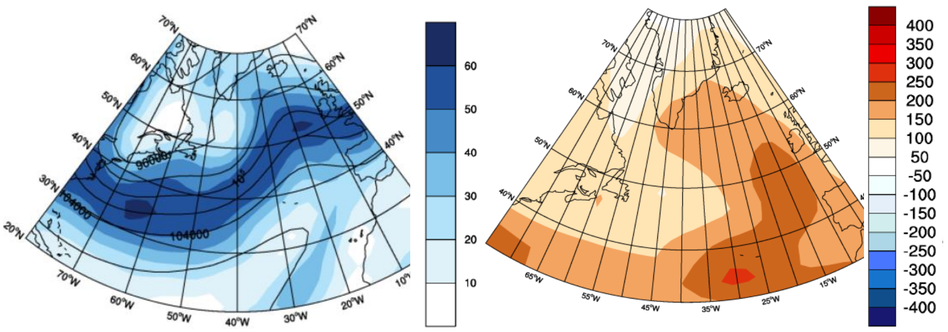

Figure 4: An example on ozone climate change functions for given weather pattern: Left: geopotential (isolines, m2s-2) and wind speed (colour, m/s); Right: ozone CCF (10-14 K/kg(NO2)[66]**. Note that the left figure has a slightly larger cut-out.**

The calculation of these CCFs requires a large amount of computing time involving a modelling chain from air traffic simulation to chemistry-climate model. Furthermore, it is not directly applicable to numerical weather forecasts as well as flight planning tools. Therefore, within another EU project ATM4E, the so called algorithmic climate change functions (aCCFs) were developed based on the CCFs from REACT4C calculation [17], [67], [68]. The aCCFs are response models, which represent a correlation of the weather system at the time of emission and the respective climate impact. An example of ozone aCCFs is given in Eqn. (1). With the temperature and geopotential knowing, one can easily calculate the average temperature response in 20 years (ATR20) for NO_x-ozone climate effects by using Eqn.(1). Similar correlations were also derived for methane, water vapour, and contrails [67], [68].

$$ATR20_{O_3} = \beta_0 + \beta_1 \cdot T + \beta_2 \cdot geopot + \beta_3 \cdot T \cdot geopot \qquad (1)$$

With β_0=-5.2e-11 K/kg-NO_2, β_1=2.3e-13 K/K/kg-NO_2, β_2=4.85e-16 K/kg-NO_2/(m2s-2), β_3=-2.04e-18 K/K/kg-NO_2/(m2s-2), T is temperature in K, and geopot is geopotential in m2s-2.

The aCCFs can easily be implemented in any numerical weather prediction model (NWP) and thereby advancing the MET-Services. A preliminary verification, where the climatology of aCCFs and the effectiveness in climate impact reduction via flight trajectories optimized using ozone aCCFs, have been conducted in ATM4E [26]. In ClimOp, we will take a closer verification of these aCCFs, which are then used to optimize flight trajectories concerning current day ATM constraints and operational boundary conditions.
Another possibility is to avoid night warming contrails since contrails contribute to more than 50% of non-CO_2 climate effects [26], [69]. The formation of contrails is purely a thermodynamic process and determined by the technology and location weather conditions. Yin et al (2018) showed that a slight detour of trajectories can reduce the formation of contrails substantially, hence largely reducing its climate impact [26]. The strategies on avoiding night contrails will be fully studied in ClimOp.

3.2.2 Lower and slower flights

Increasing flight altitude helps to reduce fuel burn, hence reducing the amount of CO_2 emissions and the associate climate impact, whereas, the altitudinal dependency of contrails, water vapour and NO_x effects is of complex scenario. For instance, the maximum net radiative forcing caused by NO_x emissions (on ozone and methane) is found at the tropical tropopause and decreases towards lower and higher altitudes [70]. Increasing flight altitude leads to an increase in contrail coverage at low latitudes, whereas, reducing the contrails coverage in mid-latitudes [26]. 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 [70].

When applying such complications on fleet level, Frömming et al (2012) showed that when flying at 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 [22]. 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 reducing 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 world fleet of a representative long-range aircraft operated on a global route network [21]. 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 (see Fig.3), e.g., 10% increase in DOC would allow about 27% reduction in climate impact.

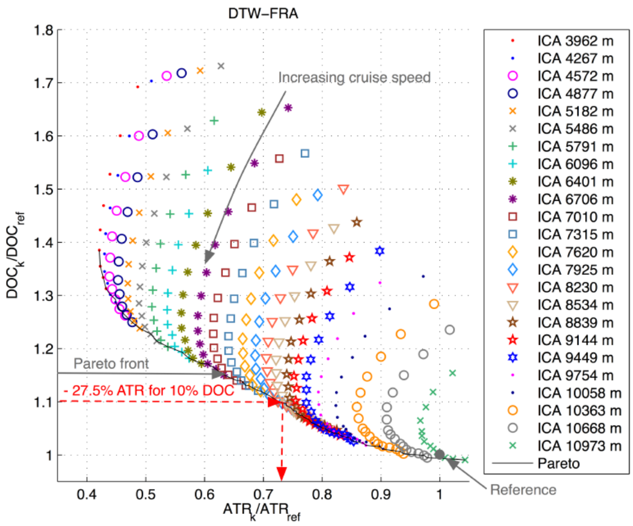

Figure 5: Pareto front for route Detroit (DTW)-Frankfurt (FRA). Mach number increases while moving down the curves for constant Initial Cruise Altitude (ICA; figure from [21]**).**

The above analysis was focused on the cash operating costs only. As the reduction of cruise altitudes and speeds provokes impacts on other areas of air transportation system, which can potentially constrain the feasibility and therefore reduce the identified mitigation potential. Therefore, the more detailed analysis is required on the feedback loops on air transport system level, e.g., on airline flight schedules, fleet size and economics including full costs.

3.2.3 Climate-optimized flight planning using satellite-based navigation

This section addresses climate-optimized flight planning as major operational improvement. Satellite-based navigation is already quite established; it is considered here to be an enabler for free routing in the context of flight planning.
Flight planning includes the lateral route and some characteristics of the vertical profile. The goal is that the objectives of the operator are met while ATM and other constraints are fulfilled. This typically consists of an anticipated simulation of the planned trajectory to estimate important key

performance indicators, such as fuel consumption (including reserve fuel) and flight time. This allows for the evaluation of the quality of the planned mission with respect to the objectives. Conventionally, the main drivers are operating cost aspects that consider fuel costs as well as time-dependent costs, but also en-route navigation charges which are dependent on the routing of the flight. Historically, airlines have to file their flight plans taking into account the available air traffic service (ATS) infrastructure, i.e. the defined route system, which itself is to a large extent still based on ground-based radio navigation aids, such as VORs, NDB etc.

Global Navigation Satellite Systems, e.g. GPS or GALILEO, enable the definition of virtual waypoints ("fixes") just by their geodetic coordinates. This laid the ground for the introduction of area navigation procedures (RNAV), especially during approach and departure. The design and the discrete structure of the ATS route infrastructure, however, still may lead to detours of the order of about 5% of the direct (great circle) distance on average globally. In order to reduce those lateral route inefficiencies, the concept of Free Route Airspace (FRA) has been developed and already implemented in some regions. FRA enables operators to freely define the route through those dedicated airspaces "on demand" such that they can reduce their inefficiencies to a minimum by defining own fixes as part of the flight route.

An important external factor, to be considered during flight planning, is wind, as wind can significantly influence the equivalent still air distance the aircraft has to fly. Wind also leads to the fact that the minimum time track for a given flight connection may deviate from the direct great circle connection. This is also known as "Zermelo problem". However, wind and weather in general are highly variable, and during a flight the wind might change such that the originally optimally planned flight route can become suboptimal. One idea to overcome this issue is to frequently update the weather information in the flight deck with up-to-date weather data provided through ground-based services, and continuously evaluate the flight plan with respect to the new wind situation. Technically, this is now becoming possible especially because of the increasingly popularity of the Electronic Flight Bags (EFB). At the time being, EFBs are equipped with the necessary software capabilities and data-link technology. If necessary, the systems can continuously re-plan the remaining part of the mission to ensure optimality with respect to the defined objectives. The wind situation may also be more beneficial on a different flight level, leading to a proposed change of the cruising altitude at a certain point. In combination with satellite-based navigation this technology provides a significant potential to increase the efficiency of a flight.

The most efficient flight plan in terms of operating cost (so considering fuel and time) is not necessarily also the climate-optimized flight plan. Here, especially the non-CO_2 emissions, such as NO_x H_2O and contrails play an important role as their impact on climate strongly depends on time and locus of the emissions. In order to minimize the climate impact of a flight, it might therefore be required to fly detours or deviate from the optimum cruise flight level. For instance, in some cases reducing the flight level by some hundred feet might already result in a strong reduction of contrail formation as flying through ice-supersaturated areas can be avoided. Those situations are very case-dependent, which requires suitable tools to allow for the evaluation of a flight plan with respect to climate impact metrics.

The former EU project REACT4C analyzed the potential to file climate-optimized flights between Europe and the US. Using so-called climate change functions (CCF, also known as climate cost functions) a multitude of alternative trajectories was evaluated with respect to the climate impact by multiplying the amounts of emissions along the trajectory with the respective CCFs at that particular location. A CCF is a function that allows for the evaluation of the climate impact of a given emission species as a function of amount, location and altitude. The resulting climate-optimized flight plans were compared to the conventionally planned (reference) flight plans for minimum costs. It was found that a reduction of the climate impact of around 25% at a cost increase of about 0.5% for westbound trans-Atlantic flights and less for eastbound flights would be possible. However, the calculation of the CCFs in REACT4C required large simulation campaigns on supercomputers with complex climate-chemistry models and was computationally very

expensive. Thus, the use of those CCFs in a real-time flight planning environment was not practicable.
The SESAR Exploratory Research project ATM4E investigated how the concept of CCFs could be extended to so-called algorithmic CCFs (aCCFs), which allow for the instantaneous determination of the CCF value at a given point in the atmosphere just on the basis of a limited number of atmospheric properties. The project demonstrated that those aCCFs can be applied on a large scale to the optimization of trajectories in Europe. For each flight not a single resulting trajectory was calculated but a Pareto front of results ranging from the minimum fuel trajectory to the minimum climate impact trajectory, which allowed for the selection of eco-efficient trajectories constituting a realistic compromise between both objectives. During this study, it was assumed that the operator will be able to file a flight plan independent from predefined route infrastructure, so purely unconstrained.

3.2.4 Climate optimised approach procedures (ITU)

Climate optimised approach procedures consist of optimizing horizontal and vertical approach routes on given objectives in terms of noise, emission, and fuel. Whereas the vertical profile can be optimised via Continuous Descent Approach (CDA), the lateral route is generated by an optimization process, which is presented below. This procedure leads to a reduction of fuel consumption and emissions. The short and long term impacts of the reduced emissions on climate will be assessed within the scope of the ClimOP project.

CDA corresponds to descending continuously by employing minimum engine thrust without levelling off. The aircraft flies at a higher altitude until reaching Top of Descent, and then performs an uninterrupted descent. By applying a CDA, the fuel consumption, greenhouse emissions, and noise nuisances near airports can be reduced [71].

For the lateral route optimization, the problem search space is defined as a set of five concentric cylinders with a merge point at the centre as illustrated in **Figure *6***. The subsequent cylinders are horizontally spaced with 5 nautical miles (NM) safety separation, and they are vertically separated by 2000 feet (ft). Each cylinder contains nodes that symbolise transition points from one level to another. These nodes are located 3 NM apart from each other for safe separation of the approach traffic. From a given entry point in the outermost ring and an exit point that refers to the merge point, an optimal route can be generated as the solution of an optimization problem with an objective in terms of noise, emission, and fuel. The solution consists of a set of nodes on the cylinders that minimizes the objective, and the process contains aircraft performance models to generate feasible routes that can be flown by aircraft and prevent loss of separation. It has been shown that the simultaneous use of the optimized lateral routes and CDA can lead to a reduction of 12% in NO_x emission, and 1.5% in fuel burn relative to the fixed-route CDA [72].

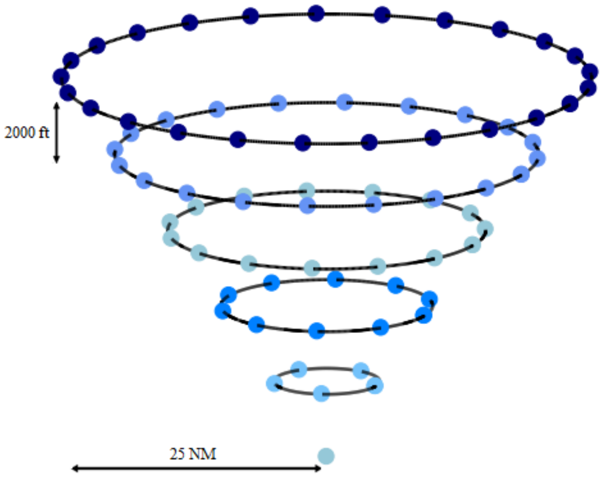

Figure 6. The concept of division of the airspace into concentric circles and nodes that act as trajectory change points.

3.3 Operational and infrastructural measures on the ground

The sustainability pathway outlined by ACI Europe pushes the airports towards achieving net zero emissions by 2050. The strategy focuses on areas where ACI Europe sees significant potential for airports to increase their performances for emissions reductions, in particular by implementing voluntary measures beyond regulatory requirements.

Within this strategy, a variety of OIs on the ground have the potential to reduce the emissions generated by fossil fuels combustion. In this context, there are airports with a certain sustainability maturity level which have implemented certain OIs mentioned in the following text, but there are also airports with a lower maturity level that may need a longer timeline and more resources to implement these OIs, which must be taken into account. These maturity levels can be related to the certification levels as defined by the Airport Carbon Accreditation[4]. However, it should be noted that these certification levels are related to CO_2 emissions, their level in terms of non-CO_2 emission levels are not covered.

3.3.1 Increased runway and airport throughput

One of the main bottlenecks in air traffic is the number of flights that can leave or arrive to an airport in the unit of time. To ensure that time slots for take-off are not missed, often aircraft have long waiting times on airport taxiways before they can depart. Similarly, holding times are experienced by aircraft before they are allowed to land or to reach their assigned arrival gate. These waiting times cause a massive waste of fuel and consequent emissions that can potentially be avoided by increasing the airports throughput and thus minimising the time the aircraft engines are in use.

This group of OIs focus on increasing the airport capacity. A strategy to increase airport capacity of up to 10% was demonstrated by the preliminary results of the SESAR2020 project PJ02-EARTH – Increased Runway and Airport Throughput [35]. Some of the solutions analysed in this framework, known as “static pairwise separation for departures”, tackled increasing departure traffic, with optimised wake turbulence separation minima, and improved separation delivery. A second group of solutions focused on the reduction of the separation of arrivals, and involved landing aircraft on closely-spaced dependent parallel runways, using staggered thresholds to help reduce wake

4 https://www.airportcarbonaccreditation.org/airport/4-levels-of-accreditation/introduction.html

separation minima and increase throughput. Other proposed strategies include the minimisation of the queuing time with a flexible runaway usage [36] and an optimised gate departure [13], and the concept of airport collaborative decision-making (A-CDM), in which information about incoming and outgoing flights is gathered and shared in real time among all operational partners, allowing them to adjust their schedules and consequently optimise the resources at airports and over the network [13], [30].

3.3.2 Efficient taxiing

Although taxi-related emissions are small compared to the total aviation emissions, required technologies are relatively mature, and required investments are relatively small. Further technical or operational improvements are required to achieve a business case that allows airlines and airports to implement these solutions, which can be achieved in relatively short time.

Airports taxi operations are geared towards safety and efficiency. Taxi operation are focussed on smoothness and safety, aiming for minimal (taxi) time between gate and take-off or landing, departure on-time performance, gate-occupation, taxi-way congestion and costs. Taxi emissions are part of local air quality studies and it contributes to climate change. However, the contribution of taxi emissions to climate change has not yet been thoroughly assessed.

To assess the climate impact of taxi operations, special attention needs to be given to consider the taxi operations as part of the full operational system. Perceived gains in taxi operation can easily be lost in the operations prior or post the taxi phase: e.g. it should be avoided that changes in taxi operation lead to in-flight inefficiencies (holding/detouring) after take-off, prior to landing or hold-ups at the gate, and it should be taken into account that additional weight for electric landing gear drives is carried on board.

The main stakeholders involved with this OIs in terms of direct actions and effects are OEMs, airlines, airports, (alternative) fuel/energy supply infrastructures, tow truck manufactures, monitoring/communication hardware suppliers, passengers, freight forwarders and governments.

The next paragraphs explore the options for reduced climate-impact taxiing, considering operational changes, introduction of new technology in both short and long term.

1. *Short term changes to taxi procedures*

The first option is to avoid aircraft emissions prior to take-off and after landing by opting for towing by tow-trucks instead of autonomous taxiing. If possible the climate impact can be minimized by looking at the overall tow-truck fuel consumption.

Independent of whether aircraft are towed or self-propelled during the taxi phases, aircraft stands, routes, and gate assignment might be allocated by minimizing emissions by taking into consideration the aircraft individual taxi and emission characteristics. Aircraft with relatively high contributions to emissions might be given the shortest route with minimal delays, be assigned different runways or be towed by tow trucks. Along the route, emissions can be further reduced by optimizing taxi-speed, minimizing braking or changes in speed and encouraged to opt for one or more engine-out taxiing (Require one or more engines to be shut down ; or enforce operational towing only if it will be technically safe and is making sense)

Beyond the actual taxi phases, operational changes to flight schedules, aircraft fleet, and procedures to select the runways in use might consider the taxi-planning process to reduce taxi-emissions and its impact.

2. *Long term changes to taxi procedures*

In the long term, infrastructure and airport spatial planning might take climate impacts on-board. This includes redesign of taxiways, holding areas, aircraft stands and gates, runway constellations etc.

Overall aircraft taxi-distance (at airport level) can be minimized. If tow truck is implemented: reduce mileage (without trailing aircraft, but of few orders of impact less that towing with aircraft); optimized planning of tow trucks and aircraft. Infrastructure: airport layout-taxiways, location of gates, tow-trucks "refuelling" stations. Efficient routing: Location of gates and stands (both for aircraft and idling tow trucks).

3. *New technologies reducing climate impact / Climate-friendly technologies*

The climate impact of taxi operations may significantly be changed by introducing new types of equipment. The new efficient taxi operations will only be effective if the energy sources for these new types of equipment are climate friendly. Using alternative sustainable fuels will reduce climate impact compared to default fossil fuels depending on the production process and transport losses in the supply chain. It should be noted, however, that these sustainable aviation fuels are still in development or certification phase, and their total environmental and climate impacts are not yet fully determined. A system approach for determining climate impact, effectiveness and efficiency is key.

– *Short term technologies*

In case of electric taxiing, there are two alternative means that are currently under development. One option is electric powered tow trucks, and an electric motor in nose or main landing gear, powered by on-board battery packs or hydrogen fuels auxiliary power unit. Note that a self-powered taxi-system loaded on an aircraft increases its weight and hence the fuel consumption in flight will increase and negatively impact climate.

– *Longer term technologies*

New aircraft might feature improved capabilities for taxi operations. The airframe structure might be better geared for high speed towing, or have a better self-propelling characteristics with one or more engines out. The airframe needs to sustain a-symmetric thrust, and capable of self-starting engines with shorter warm-up and cooling down features. Engines might be improved by reducing emission at taxi-thrust levels.

In order to implement these OIs successfully, the success factors and adverse impacts need to be identified, which will be relevant in implementing and assessing the OIs. In order for these type of OIs to succeed, stakeholders need to continuously coordinate the requirements and progress. Furthermore the infrastructure needed for these type of OIs need to be available, including monitoring and planning systems. Additionally, it is crucial to obtain a sound scientific understanding of climate impacts of individual species and their interactions with each other, as well as their air quality aspects. When designing implementation strategies for these OI's it is important to take into account that there is a risk of pushing adverse effects and system efficiencies beyond the taxi-processes. Furthermore it should be noted that more efficient taxiing may offer room for additional capacity or movements and risk of congestion, which results in a negative impact on climate.

3.3.3 Electrification of ground equipment for airport operations

As to Climate Change Mitigation, besides suggesting following the best practices implemented through the *Airport Carbon Accreditation* programme, the Resolution issued by ACI EUROPE on 26 June 2019 provides that European airports:

- Call on the aviation industry, ICAO and governments to work towards net zero emissions aviation,

- Commit to reach net zero carbon emissions for operations under airport operators' direct control(Scope 1 and 2)[5] by 2050,
- Call on governments to accelerate, where relevant, the transition towards a clean energy system as a key enabler for airports to reach net zero emissions.

In terms of innovation, a focus is needed on actions aimed at decarbonizing the aviation sector as a whole, in particular on initiatives relating to sustainable aviation fuels (SAF) and the electrification of airport and aircraft operations.

ACI Europe Sustainability Strategy for Airports [73] provides a general direction and guidance to the sustainability efforts of European airport operators aiming at realizing a shared vision of the sustainable airport of the future. Airports are immovable facilities, embedded in their territories: each airport is unique, has specific characteristics and operates within a specific context, this is why the ACI Europe Sustainability Strategy does not define a mandatory list of sustainability related actions and activities, does not establish reporting requirements nor metrics for airports.
The sustainability pathway proposed in the Strategy for Climate Change Mitigation and Local Air Quality improvement at airports is structured around 4 steps: Launch, Development, Maturity and Leadership.

The first step of the sustainability pathway proposed for Climate Change Mitigation and Local Air Quality improvement, "Launch", is the analysis and assessment of all the operating vehicles in the Land Side Area and especially of the Ground Support Equipment (GSE) in the Air Side Area. The Air Side area is entire zone of an airport that is past the customs control, passport (check-in) and security check zone. The area includes all areas accessible to aircraft, including runaways, taxiways and ramp.

Chapter 2.5 "Ground support equipment" of the ICAO Document 10013 [74], besides specifying that the terminology GSE refers to the broad category of vehicles and equipment that service aircraft, including those used for towing, maintenance, loading and unloading of passengers and cargo, providing electric power, fuel and other services to the aircraft, provides a quite complete list.

The types of GSE common to all Airports are:

1. *Aircraft tractors*. Aircraft tractors, also known as aircraft tugs,
2. *Air-conditioning units (ACU)*. Air-conditioning units are trailer- or truck-mounted units used to supply preconditioned air to stationary aircraft at the terminal and also during maintenance,
3. *Air start units (ASU)*. Air start units are trailer- or-truck-mounted compressors that provide compressed air for starting an aircraft's main engines. Air starts are typically used only when an aircraft is not equipped with an auxiliary power unit (APU) or when the APU is not operational,
4. *Ground power units (GPUs)*. Ground power units provide 400 Hz of electrical power to aircraft when the aircraft's APU and the main engines are not operating,
5. *Baggage tractors*. Baggage tractors are used to transport luggage or cargo between aircraft and terminal(s),
6. *Belt loaders and container loaders*. A belt loader is a self-propelled conveyor belt used to move baggage and cargo between the ground and the aircraft,
7. *Lavatory service trucks and carts*. Lavatory trucks are normally equipped with stainless steel tanks, a pump and a hose used to service aircraft lavatories,

[5] Carbon dioxide emissions are subdivided as follows:
- Scope 1 - Direct emissions associated with sources owned or controlled by the Group's companies, such as fuels used for heating and operational equipment necessary for airport activities.
- Scope 2 - Indirect emissions associated with the generation of electricity or thermal energy acquired and consumed by the Group's companies.
- Scope 3 - Other indirect emissions deriving from the activities of the group's companies but produced by sources not belonging or not controlled by the companies themselves, such as personnel work trips and home-work travel.

8. *De-icers*. De-icers typically consist of an on-road truck equipped with tank, pump, hose and spray gun to transport and spray de-icing/anti-icing fluid on aircraft,
9. *Lifts*. This broad category includes forklifts, scissor lifts, and loaders that allow access to the aircraft for servicing at the terminal and at the maintenance base,
10. *Passenger ground transport*. Passenger ground transport includes passenger buses, passenger steps and mobile lounges (which replace buses and steps).

Electrification may require a substantial investment in infrastructure. The usage of electric GSE significantly reduces ramp emissions although the heaviest GSE, such as the De-Icers, the Lifts, cargo loaders, some cargo tractors, and some aircraft tractors might not be able to meet heavy duty requirements.
An important aspect of the electrification implementation is the charging methods: besides standard charges airports have to consider installing rapid-charge stations. These will have to be logistically placed so equipment operators can conveniently plug in whenever the vehicle is not in use. To find the best strategic locations, it will be important considering:

- Airport configuration and regulations
- Traffic patterns to and from stations
- Sufficient power supply
- Appropriate operational room

Another opportunity that is being evaluated especially for small and large airport vehicles (both Air Side and Land Side) Is the usage of electro engines powered by fuel cell/hydrogen. Currently the production of "green" hydrogen takes place in an environmentally sustainable way and completely free of CO_2 emissions from renewable energy (for example hydroelectric or photovoltaic energy).
The transition to hydrogen vehicles depends on the construction of new infrastructures and on the competitiveness of prices which will be made possible through the introduction of an adequate number of pieces on the market.

3.3.4 Renewable energy production at the airport

The Resolution formally committing the European airport industry to become net zero for carbon emissions under its control by 2050 was launched on the 26th June 2019, at the 29th ACI EUROPE Annual Congress & General Assembly in Cyprus. As the Net Zero concept does not allow for carbon offsetting, with the purpose of supporting Airports towards accelerating the clean energy transition at Europe's airports to reach NetZero by 2050 for carbon emissions under their control, on 2nd October 2019, ACI Europe signed an agreement with the RE-Source Platform, the European alliance of stakeholders for corporate renewable energy sourcing [75].

With the aim of strengthening the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and reducing carbon emissions, it is essential to start producing electricity from so-called renewable sources.
A series of alternative renewable energy sources have been identified that can be used without having to worry about them running out one day.
The list of available renewable energies includes: geothermal energy; hydroelectric energy; marine energy; solar energy; wind energy; biomass energy; waste-to-energy; energy or cogeneration from groundwater.

ICAO's Eco-Airport toolkit: "A Focus on the production of renewable energy at the Airport site (2019) provides a useful survey on renewable energy at airports [76].
After considering energy conservation measures the next step is an evaluation of the possibility of producing and using alternative sources of energy. Several renewable energy options exist for airports, including:

1. Hydropower. The most common method of hydropower generation involves construction of dams on rivers and releasing water from the reservoir to drive turbines. Hydropower is a potential source of renewable energy at airports. The electricity is created in a process by which high water pressure forces a turbine to spin. The water flow can be controlled and electricity output altered to match the airport's needs. This option would require a location near a water source.
2. Wind. Wind is the second most widely used renewable energy source in the world. Although this resource is not available in equal measure right across the planet, the use of wind energy is particularly attractive as, compared with other energy forms, it does not emit greenhouse gases, it is limitless, and it is clean. Wind energy generation on airport ground is still relatively novel in its application due to a number of technical barriers with respect to the safety of aircraft operations. Wind turbines, which transform the kinetic energy of the wind into electricity, are capable of meeting substantial electricity needs. Turbine installation and use necessitates extensive safety assessments, as they may be considered (alongside other tall objects) capable of penetrating the navigable airspace in close vicinity to airports and generate interference issues with safety critical communication, navigation and surveillance infrastructure. In light of this, alternative design options may be considered (e.g. wind turbines with vertical axes).
3. Solar. Because of the enormous amount of solar radiation reaching the top of the Earth's atmosphere (approximately 1400 Watts per square meter at any given time), solar energy is an important renewable source but major investments are required compared with other energy generation systems.. Photovoltaic (PV) systems have been installed at more than 100 airports worldwide and are well-suited for many existing airport designs due to the vast horizontal surfaces on which they can be installed. They can be mounted on terminal buildings or placed on unused or otherwise unproductive airport property. Some airports have even used the harnessed solar energy to power ground vehicles or to deploy charging stations for electric cars in parking areas. PV systems that supply power for at-gate operations have furthermore been granted eligibility under the Clean Development Mechanism (CDM) framework. In some cases, however, PV systems may present challenges with regards to solar glare, and the airport must consider the operational safety implications for their specific location and proposed project.
4. Biomass. Bio-power is the fourth biggest renewable power source after hydro, wind and solar. Biomass energy can be produced by any material of organic-vegetable origin (trees, plants, farming or industrial waste, urban waste). Biomass energy is another option for airports depending on the availability of feedstock supply chains. Biomass is converted into fuel offering a variety of applications at the airport site, including heating and cooling of terminal buildings and electricity generation. The fact that biomass derives from a comprehensive (and progressive) list of materials makes it necessary for the individual airport operators identify the relevant sources that are most feasible to its operational and commercial context..
5. Geothermal. Geothermal energy is produced by exploiting the energy of the heat in the deepest layers of the Earth's crust. It is obtained by channeling the steam deriving from the subsoil into turbines which are used to produce electricity and by recycling the water vapor produced to heat buildings, for greenhouses and for various uses in heating systems. Geothermal energy systems are capable of heating and cooling airport buildings. For terminal heating and cooling, airports can pump low-temperature water from underground water tables for circulation in on-site air heating and cooling systems. However, these options are highly contingent on the airport's geological conditions. The greater part of these systems are below the ground and therefore do not disrupt aeronautical operations (provided that the facility above ground is not blocking visual and navigational aids), though, they are often complex to

install. Consequently, airport projects with geothermal energy are typically most worthwhile executing in combination with the construction of new facilities or a major refurbishment of existing airport structures.

The practical application and development of the above renewable energy options depends mainly on the characteristics of the individual airport such as its physical settings (e.g. geography, geology and climate), together with its operational and economic reality.

3.3.5 Monitoring system for the atmospheric emissions

In Europe the majority of civil airports are located in the surroundings of larger cities with a number of citizens exposed to high level of noise and emissions of pollutants. Atmosphere in proximity 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 but also to external elements like roads, buildings and factory plant with whom an airport shares the principal chemical substances emitted (i.e. Particulate matters, Nitrogen dioxide, Carbon Monoxide….).

Separating the airport emissions from other sources is the main issue in managing this externality at airport level. Compared to airport environmental noise, aircraft emissions of pollutants are more difficult to identify for these multi-source conditions but also for a less defined procedure in developing a monitoring system. While noise monitoring systems are planned following specific guidelines and rules (i.e. noise devices placed under Airport SID and connected with ATM), monitoring systems for atmospheric emissions have less conditions related to aircraft and airports.

Therefore, the emissions monitoring system should also be regulated in order to be able to assess and compare the same parameters, even if airports are different .
This would constitute an important Operational Improvement.
At the moment, the evaluation approaches adopted might vary, and the evaluation tool is the monitoring stations.

Generally an emissions monitoring system could be defined by a number of fixed monitoring stations placed in significant airport zone in order to analyse some specific sources like ground operations and GSE but also measuring the global air quality of the airport. Data collected in specific server could then be published. A weather monitoring station is also necessary to correlate substance concentrations with weather condition. This procedure needs high cost of maintenance and could be not an option for smaller airports.

Another approach focus on mobile measure campaigns to analyse specific operational scenario or different pollutants. This method could be more flexible and even more precise when a specific category of pollutants is analysed. These campaign are influenced both by the specific period where they are done and the limited interval of time of measures so it is necessary to plan a specific number of campaign in order to cover the annual dynamics in pollutant concentration trends.

All these aspects specify that every airport should implement its emissions monitoring system taking into account a considerable amount of variables taking into account both environmental and economic parameters maybe integrating measured data from devices with simulated scenario calculated with emission models.

3.4 Operational measures at regulatory level

The concept of protecting the climate through regulation of operations is relatively novel. Technical concepts have experienced more focused, for example, up to recently the ICAO Committee

Aviation Environmental Protection has focussed on engine emissions certification targeted towards local air quality (e.g. NOx). Recently aircraft are certified to the new CO_2 standard that addresses climate concerns. A market based mechanism, CORSIA, aims to reduce CO_2 emissions from operations; in practice the CO_2 emission are expected to be offset outside the aviation sector.

Non-CO_2 climate impacts are not considered yet in regulations. Until today, operations itself are not directly subjected to climate impact regulations. Regarding operations, ICAO has focussed on regulations for safe and smooth operations (such as PANS-OPS). Hence, no regulations exist on aircraft operations that specifically aim to reduce climate impacts based on non-CO_2 emissions.

Given the urgency to mitigate climate impact, it might be well feasible in the near future to discourage operations for the purpose of mitigating climate impacts beyond CO_2 emissions.

There are two types of regulations:

1. Market based systems, where measures introduce changes to costs components in the system. Stakeholders will often seek to minimize or compensate these additional costs by adjusting fleet and operations or make changes to the supply chain (e.g. fuel).
2. Standards that aircraft or operations need to comply with. Aircraft certifications standards already exist for CO_2 emissions, but for non-CO_2 emissions or operations specifically w.r.t. climate impact, standards do not yet exist.

It may be worth while exploring aircraft operations for the mitigation of non-CO_2 effects, as adaption of operations might also be feasible for older aircraft for which technical improvements are not feasible on the short term.

These regulations have to work hand in hand with a realistic and appropriate cost benefit analyses (CBA) and at the final end a smart business case (BC) plus strict governance.
IATA and the AUs have already invested a lot of money for the **M**ost **C**apable **B**est **S**erved (MCBS, former BEBS) Ideas. To facilitate the optimum green flight paths that will deliver environmental and economic benefits by reducing fuel burn, emissions (CO_2), noise and fuel costs, IATA and AUs tested, developed, introduced and deployed into ICAO & SESAR:

- Operational incentives leading to fleet equipage in support of the Airspace Concept,
- Provides for immediate benefits, traffic permitting,
- Enhanced and accelerate system performance once past the ‘tipping point’.

3.4.1 Limit "climate unfriendly" aircraft operations

The climate impact of a single flight is dependent on a combination of route, flight profile (combined with the flight trajectory), and aircraft properties together with the atmospheric properties along the flight trajectory. Whereas the impact of CO_2 is independent of location (longitude, latitude and altitude), the impact of other non- CO_2 species dependent on the location, hence flight trajectory, time of the day and humidity (for contrails). The amount of emissions depends on aircraft and engine type in combination with thrust setting, in turn depending on aircraft weight, speed and altitude.
This observation might lead to regulations that promote more friendly operations including all relevant aspects of the operation and local state of the atmosphere.

From a regulatory point of view, several options exist to promote climate friendly aircraft operations:

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. This can be done over different scales, such as on a per flight, per airline or country basis. To implement this, a monitoring system to track and predict climate impact is required, which is not yet available (see Sect 2.5.1).A more simple approach would be to take certification data (e.g. CO2 standard) as a proxy. Generally speaking, and if well implemented, market mechanisms principally ensure the

maximum transport capacity given limits to impact. It encourages the agility and flexibility of stakeholders to cope. Note that mitigation of measures might come in two different ways:
    a. closed market where the allowances (impacts) may be traded only between stakeholders within the aviation industry,
    b. open market where allowances (impacts) may be traded with impacts from other types of industry;
2. regulations that restrict certain aircraft operations in certain parts in the atmosphere at certain timeframes, to reduce climate impact. This approach could follow the concept of a route clearance or the concept of restricted airspace where special clearance including speed and altitude restrictions must be obtained from the controlling agency obtained directly or via ATC. However, this approach requires a system to monitor the local atmospheric conditions, in conjunction with limits to provide clearance.
3. route clearance/restricted airspace for climate sensitive areas without a monitoring system for the actual climate conditions in place. This implies a more general approach.
4. regulations that impose direct specific flight procedures on some flight segments. Examples are:
    a. While taxiing, require one or more engines to be inoperative; or enforce towing.
    b. Limit speed and/or altitude to keep momentary emissions within limits based on the local atmospheric conditions similar to noise abatement procedures like doc29 [77], extended to cruise).

There are several time scales to be considered for the implementation of new, climate friendly regulations of operational phases:

- Long term, strategic planning (on a year by year basis) by limiting the number of flights in climate-sensitive areas and hence reduce the climate impact.
- Short term tactical (day to day) planning by maximizing/rerouting a number of flights based on monitored atmospheric properties a few days in advance.
- Ultra-short term (minutes to hours), where during flight, aircraft are given ATM guidance to reduce their impact locally.

Regulations to promote climate friendly operations might consider some prioritisation based on aircraft (certification) properties or planned routing and profiles. Suitably selected KPI's will support and objective judgement.

A proper implementation of those regulations will see stakeholders to be stimulated to foster climate friendly aviation. For example, OEM could aim to produce aircraft that meet or are adaptable to the new climate standards. Airlines could consider to (in addition to existing economic pressures to minimize costs) adjust fleet to more climate friendly aircraft, reassign aircraft to flights taking into account the regulatory aspects or reroute flights by adjusting hub and spoke systems and thereby avoiding climate sensitive areas. Air traffic management (and Air navigation providers) will seek to adjust operations and install monitoring systems to determine the state of the local atmosphere and predict the impact of a flight passing through compared local thresholds for e.g. contrail formation. 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.

In order to ensure a transition period to the introduction of policies, airlines and OEM may be granted free allowances, or grandfather rights regarding climate performance.
It must be recognised that such a system is quite complicated because all stakeholders will need to take collaborative decisions and share information. Care should be taken that the system is feasible, and seamlessly integrated into air traffic management while avoiding adverse effects e.g. (non-) carbon leakage.

3.4.2 Environmental scoring

With this OI priority is allowed to aircraft operations/routes/procedures which are highly climate-friendly to those who are less climate-friendly. By prioritizing climate friendly operations (aircraft, flight or ground operations), these are stimulated and the less climate friendly operations will be phased out on the long term. So this has two effects: on the short term the climate friendly operations will be prioritized, thus a short term positive impact can be seen, and on the long term the less climate friendly and climate unfriendly will make space for even more climate friendly operations as those will be stimulated. So on the long term a larger impact will be seen. The goal of this concept is similar to the operational improvement discussed under (3.4.1), but here the concept is aircraft focused as opposed to flight focused.

Environmental scoring promotes monitoring, objectivity and information purposes to allow potential travellers to better guide their decision to travel. The environmental scoring is geared towards information for the general public. Scoring implies that KPIs are represented in a format easily understandable by the general audience.

If environmental scoring is used as climate prioritisation, (sets of) KPIs will be designed and used that allow environmentally rank flights from best to worst. A flight includes aircraft type, flight profile and route and the actual environmental impact of CO_2 and non- CO_2 along the route. This might be quite a challenge. Environmental scoring refer to the climate impact, and optionally include the transport capabilities (tonne-km, pax-km or alike) allowing to consider trade-offs.
Environmental scoring might be a mechanism to gather KPI's for the purpose of guiding operations.
If environmental scoring is used as climate prioritisation, (sets of) KPIs will be designed and used that allow environmentally rank flights from best to worst. A flight includes aircraft type, flight profile and route and the actual environmental impact of CO_2 and non-CO_2 along the route. This might be quite a challenge. Environmental scoring refer to the climate impact, and optionally include the transport capabilities (tonne-km, pax-km or alike) allowing to consider trade-offs.

Environmental scoring might be a mechanism to gather 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. regulate that flight operations with higher scores have priority over flight operations with lower scores.

In order for this OI to be implemented effectively, the Government, ATC and airports need to cooperate and take responsibility. Airlines need to be able to adapt to the new regulations and it shouldn't cost them too many losses. This might need to be nudged or supported by regulatory bodies to move it in right direction in the start-up phase.

3.4.3 Environmental charges and incentives

Environmental charges introduced for climate unfriendly operations and incentives for climate friendly operations. This could be in terms of aircraft operations, flight operations or routing options.

1. **Focus on aircraft operations**
   To introduce charges and incentives on aircraft operations to motivate the usage of climate friendly aircraft operations.
2. **Focus on flight operations**
   To introduce charges and incentives on flight operations to motivate the usage climate friendly flight operations.
3. **Focus on routes**
   To introduce charges and incentives on certain routes, or route sections, to motivate the usage climate friendly routes.

Charges imply a trade-off between economics and environmental impact where economically beneficial changes will be paid depending on the impact on climate. It is of prime importance to set the right rates. In this way stakeholders are motivated to operate in a climate friendly way and developments towards a climate friendlier aviation industry are motivated.

The principle of *First-Come-First-Served* has served the aviation community well for many years. However, this principle has become increasingly problematic, especially in periods of technological transition, when there are still significant numbers of less capable users. For airlines, the most important objective is to have an ATM system that has the greatest capacity, commensurate with the demand, and for it to operate with the best possible and greenest efficiency. The *First-Come-First-Served* principle is not compatible with this objective anymore.
The choice of operating under a Most Capable Best Served (MCBS) concept requires an understanding of overarching principles that must be followed for a successful outcome. IATA supports the principles contained in the ICAO Global ATM Operational Concept as described in ICAO Doc 9854.

Revenues of charges might be channelled to foster investments that mitigate or negate adversary climate impacts.

For the implementation of these OI's, the following options will be considered for the aforementioned three categories, based on internal discussions of the consortium:

1. **Focus on aircraft operations:**
   - charges on usage of climate unfriendly engines or other parts,
   - incentives on usage of sustainable drop-in fuels,
   - charges on tankering (or generally, excess weight (water, equipment etc.),
   - selection of aircraft type.
2. **Focus on flight operations:**
   - incentives for CDO and CCO,
   - taxi operations,
   - flying lower and slower, mitigation of associated costs,
   - scheduling (because the impact might vary with time (hour, day, seasons),
3. **Focus on routes:**
   - charges on flying through climate sensitive areas,
   - incentives on flying climate friendly routes,
   - selection of destination,
   - network development (hub-and-spokes, vs point-to-point operations).

The European Parliament have asked, in 2017, the SESAR Joint Undertaking (SJU), additional & regular updates of the standard ATM Master Plan, to develop a so called Airspace Architecture Study (AAS) and later the related AAS Planning. Both important initiatives have been published already in the years 2018/19.

In any operational concept where flight capabilities play a significant role, it is of critical importance that the entire design and implementation process be transparent and harmonized with other similar initiatives (CARAT or NextGEN) so as to not distort business cases and worldwide flight Airline operations and Aircraft usage.
In order for these OI's to be successfully implemented, the government must take responsibility in organising the financial and operational infrastructure for these OI's, such as a monitoring and administrative system. Furthermore, the legal implementation lies in the responsibility of governments as well. Charges and incentives must also not lead to misuse or loopholes to even more climate unfriendly operations.

Recently, the expression "*Best Equipped Best Served*" has been used to describe a mode of operations where those aircraft operators that have invested in modern aircraft equipage would be allowed to take full operational advantage of their investment. Enabling operations under this principle is more difficult than it may appear at first; mostly due to the complexity caused by mixing aircraft capabilities within dense airspace and the consequential workload increase on air traffic control. Also, “best equipped” is not the best indicator of a flight’s capability. Several other elements such as flight planning capability, crew training, etc. must also be considered.

IATA and ICAO prefer to support a migration towards *Most Capable Best Served* with the intent of optimizing the efficiency of airspace operations. Under this principle, those operations, supported by technology, qualified personnel, and systems on the ground and in the air, that provide the best operational benefit and incentivize evolution towards agreed-upon objectives, would be preferred. Typically, the most capable flights would be provided the opportunity to gain full advantage of their capability in order to maximize the overall efficiency of the ATM system and of the flight itself. “Most Capable” is a term that regroups aircraft equipage, crew training, operational certification, flight planning capability and the ability to efficiently and seamlessly convey the pertinent capability to ATM.
This concept rests on the following pillars:

- Collaborative Decision Making regarding Airspace Management and the required capabilities,
- Equipage incentives, whether financial or operational or a combination thereof,
- Regulator willingness and ability to certify advanced aircraft capabilities,
- Equitable access to airspace, viewed on a longer time scale.

It is important to continuously discuss this MCBS or BEBS concept as it will set the tone for the evolution of ATM and is directly linked to the economic debate (who pays for the ATM/avionics investment and how) and ANSP performance improvement. Although the debate is currently primarily focused on NextGen and SESAR, determining which flights are *Best Served* has a global application. It is therefore critically important that there be common agreement on the definition, understanding and application of *Most Capable Best Served*. Different State or regional applications of *Best Served* would cause significant problems for international carriers.

4 Criteria for Operational improvements selection

The main objective of this deliverable is to identify and rank a set of OIs that result in a climate impact mitigation while balancing the interests of the various stakeholders defined in table 1 of this deliverable. OIs that have been defined in this document encompass operations that are about to be deployed but also those that are more radical and have not been considered in detail before. The main priorities for any given OI are climate mitigation potential, time, cost, safety and application through policies without disrupting the balance of the stakeholders. The preliminary assessment of OIs for WP1 will be reported in D1.3 where the potential benefits and shortcomings of each defined OI is evaluated with respect to the KPIs documented in D1.1.
Figure 7 shows the timescales and feasibility of the chosen OIs with respect to one another. There are no exact quantities attached to this figure because each OI may consist of multiple concepts that differ in scope. Each colour represents the four OI categories discussed in Section 3.2-3.5.

Two significant trends emerge in this figure, 1) is the correlation between feasibility and timescale, and 2) the clustering of OIs related to “operational measures at regulatory level.” Feasibility is combination of several factors including technology readiness, investment cost, deployment scale, and regulatory restrictions. There is a natural tendency for feasible solutions to be implementable in a short time. Conversely, if the solution is less feasible, then it will require more time for implementation. Hence, this tendency is observed by the general trendline the OIs follow.
Secondly, while most OIs are scattered along the trendline, the ones from “operational measures at regulatory level” are clustered together at relatively feasible, short timescale quadrant of the figure. This clustering is a result of the top-down level approach of these OIs. The government or some other regulatory body dictates the rules or infrastructure, and everybody essentially has to

follow. The challenge arises when these regulatory measures are implemented or enforced at a global level. Then all actors must agree upon the details before enforcement which shift the timescales to a longer period. There may be differences in terms of the level of bureaucracy among the OIs. However, generally speaking, these OIs have already been implemented on a small scale and requires further research on how to scale it up.

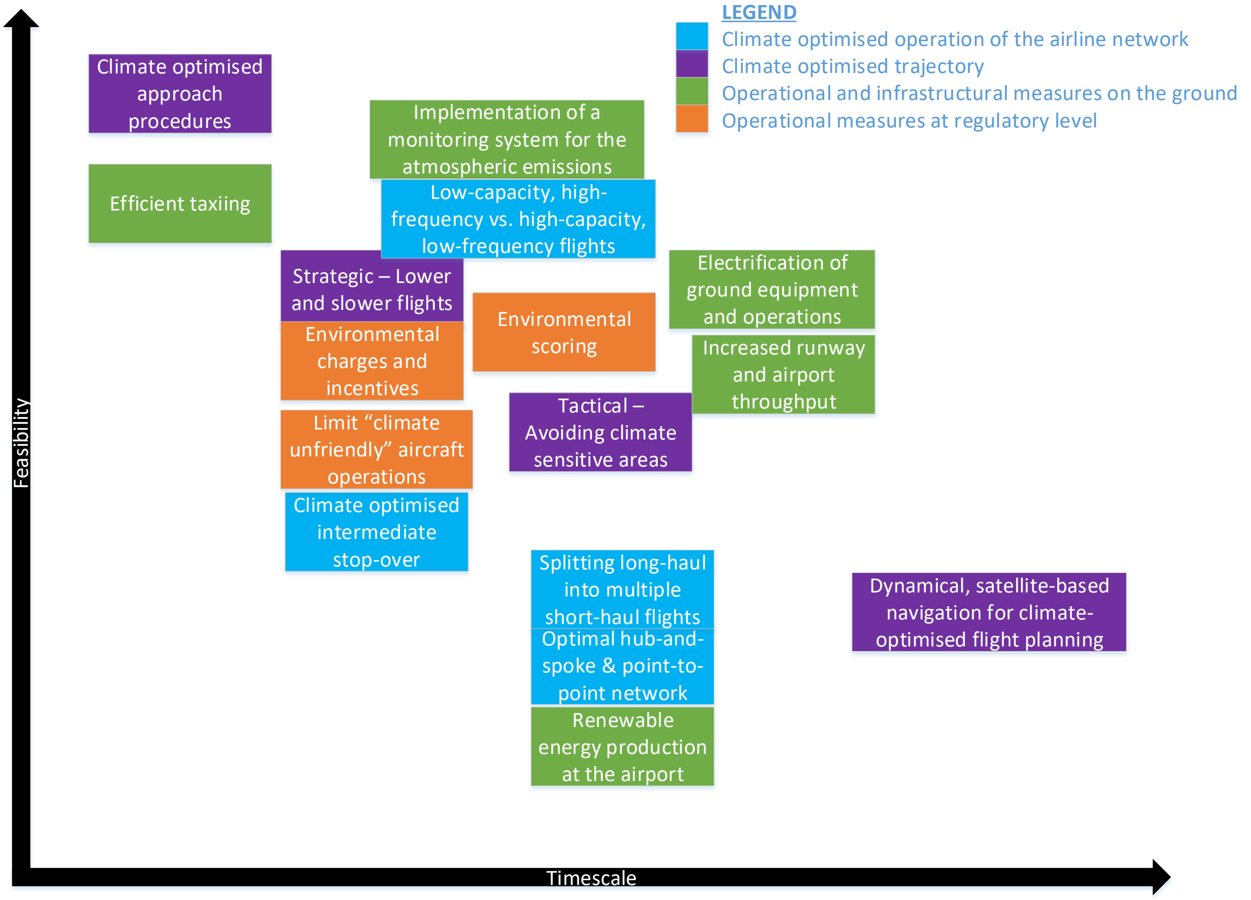

Figure 7 - Initial estimation of relative timescale and feasibility of the selected OIs.

5 Conclusions and future work

This document reports on the results of the review of the existing literature about the operational improvements (OIs) to mitigate the impact on climate of the aviation sector by reducing its CO_2 and non-CO_2 emissions. The main sources of the proposed OIs are scientific papers, public documents, statements of intents, and conference proceedings issued by airlines and airports associations, researchers on aviation, and regulatory bodies. This detailed review has been complemented with the knowledge and expertise of the ClimOp partners, and the results of a dedicated ClimOp Consortium workshop held in February 2020 at the Delft University of Technology. As a result of this process, 47 OIs were identified that have the highest potential to reduce the negative impact of aviation on climate.

The list of selected OIs consist of actions and measures to be implemented at all levels of the aviation operations. These include the ground operations, the airport activities and infrastructures, the departure and approach procedures, the cruise phase of the flights, and the measures that can be introduced or fostered by the regulatory bodies. The OIs described in this document are characterised by significantly different levels of maturity and consequently different timescales for their introduction in the every-day operations. Some measures are about to be, or are currently being, deployed: for example, the increasing upgrade of existing infrastructure according to energy efficiency criteria, a more flexible use of the airspace and sectors for reduced flight durations, or the attempts to reduce fuel consumption with an optimised gate departure, and collaborative decision-making. By contrast, other measures are expected to have a positive impact but will require longer timescales to be deployed, such as a climate-based flight planning and routing, the complete electrification of ground equipment, measures to increase the airport throughput, or the shift from high-frequency, low-capacity flights, to lower-frequency, higher-capacity ones.

The next steps of the project will be to rank the identified OIs according to their potential to reduce the impact of aviation on climate, and to preliminarily assess them against the Key Performance Indicators selected in the deliverable D1.1. Such assessment will be undertaken with the support of the Aviation Stakeholders involved in the ClimOP Advisory Board. This analysis will be documented in a future deliverable D1.3 and will be preparatory for the study to be conducted within the Work Package 2 of the ClimOp project. In this upcoming study, the impact of different OIs, or combinations of OIs, on the climate and on the relevant aviation stakeholders will be quantified with different modelling tools.

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