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Airline Network Planning Considering Climate Impact: Assessing New Operational Improvements

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Abstract: The aviation industry has set an ambitious goal of reducing its climate impacts. Accordingly, airlines must balance their plans according to this goal with financial considerations. We developed a multi-objective framework to facilitate climate-aware network design by incorporating the objective to minimise the flight average temperature response (ATR) when optimising the airline network. We also assessed the operational improvements (OIs) which are introduced to improve sustainability in airline operations. In particular, we considered intermediate stop-overs (ISOs) and lower flight altitudes as OIs in our case studies. We analysed the impact of considering the climate impact in the planning of operations of three different airline types: one main-hub-and-spoke (KLM), one smaller multi-hub airline (TAP), and one low-cost carrier (EasyJet). The results show that airlines could also lower their environmental impact by 10–36% when considering the ATR as an objective. However, this would require an 8–20% reduction in profits. Adopting lower-altitude flying with ISO could mitigate their climate impact by 27–49% while reducing profits by approximately 6%. Our study highlights the importance of considering the airline network as a whole and demonstrates the potential benefits of operational improvements from a network perspective.

Keywords: network planning; climate impact; non-CO_2 effects; intermediate stop-over; average temperature response; multi-agent systems; dynamic programming

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1. Introduction

Following the United Nations Framework Convention on Climate Change (UNFCCC) guidelines, in order to maintain a global mean temperature rise of 1.5 °C above pre-industrial levels or less by 2030 [1,2], substantial efforts must be made to reduce CO_2 and non-CO_2 emissions through greener strategies and operations. Therefore, the sustainability of operations is increasingly becoming a critical factor for many industries. This is the case for the aviation industry, responsible for 2.4% of CO_2 emissions and 3% of the EU total greenhouse emissions according to [3]. The actual aggregated amount could even be above the mentioned values by including all non-CO_2 species [4,5]. The effective radiative forcing induced by non-CO_2 such as nitrogen oxides (NO_x) or contrail-induced cirrus makes up approximately two-thirds of the total aviation climate impact [6]. In contrast to CO_2 emissions, these effects depend not only on emission quantities but also on emission location and atmospheric boundary conditions [4]. These contributions have more than doubled in the past 20 years and are expected to continue to increase in the future due to the significant traffic growth despite the aircraft's airframe, engine performance, and operational improvements. Eventually, aviation emissions change the atmospheric concentrations of greenhouse gases and cloudiness, leading to an atmospheric radiation imbalance resulting in temperature changes. Climate metrics, e.g., the ATR [7], are used to evaluate the climate impact of aviation scenarios.

The topic of mitigating the climate impact of aviation has been addressed in the academic literature in several studies. Based on the holistic overview offered by [8], there are three main research directions which are contributing to aviation climate impact mitigation. Firstly, there are sustainable energy resources advancement, as discussed, e.g., in [9,10]. Secondly, novel aircraft design and aircraft performance improvements, are addressed, e.g., in [11–13]. Finally, there are operational improvements (OIs), which address the utilisation of the currently available fleet and technologies to improve aviation climate impact, as considered, e.g., in [14–16]. The first two research directions have mainly had a long-term impact on aviation. With the exception of sustainable aviation fuel (SAF), which is already used on a small scale by some airlines, it should take more than one decade for new aircraft designs or hydrogen-powered aircraft to start operating in the airline fleet [17]. They are not expected to contribute to the effort of reducing the aviation footprint in the short term [8]. Aviation stakeholders, particularly airlines, will have to adopt climate impact reduction goals in their decisions using current technologies to improve the sustainability of their operations. One way to do this is to rethink their operations and adopt OIs. These are changes in the operations that modify the airline processes and services to improve their operational efficiency and simultaneously mitigate the climate impact. In this paper, we particularly looked at OIs that can reduce the climate impact of airline operations.

One well-studied OI is the concept of ISO. This OI aims to reduce the stage length of flights by performing one or more intermediate landings during a mission. Past studies on the ISO have covered the analysis of limited missions approaches [18,19] and global-level assessments [16,20]. These studies primarily evaluated the potential fuel savings and climate impact mitigation that could be achieved, suggesting fuel savings of between 4.8–14.0% [16] and climate impact reduction up to 40% [20]. Some studies considered new aircraft designs to better suit ISO operations [18,21]. The fuel efficiency gains, in these cases, can be significantly higher, eventually doubling the values from the studies not considering aircraft redesign. Modifying the flying cruise altitude in the interest of climate impact reduction is another promising OI. As atmospheric chemical processes are highly sensitive towards the emission altitude, flying lower (FL) has a great potential to reduce the flights' climate impacts [22,23]. Studies of this OI show that FL can decrease the climate impact up to 33% [15,24,25]. The combination of ISO and FL is another research aspect that may increase the advantages of both OIs in mitigating the climate impact.

It should be noted that the previous research related to these two OIs either considered a single-flight mission or assumed that airlines' fleets, networks, and flight schedules would remain the same after implementing these OIs. The reported increase in flight time and costs may affect the planning decisions of airlines, resulting in different network and fleet allocations, and compromising the assessment of the impact of OIs. Such assessments can only be performed using airline network planning models, including network decisions.

Many airline network planning studies are present in the literature, considering both fleet planning [26,27] and network development [28,29] to achieve fuel and climate cost minimisation.On the other hand, considering climate impacts while solving the network planning problem has not been fully explored. The work in [14] developed fuel and climate cost minimisation networks before optimising the flight trajectories of the aircraft operating the flights in both networks. There are few details about how the airline network and passenger flows were modelled. Nonetheless, the results suggest that only direct passengers were considered, and the flight frequencies per route were obtained. The study from [30] integrated the fuel and emissions per potential route in the network to optimise the airline network while considering both the profit and ATR. The authors used a mixed integer linear programming model (MILP) to optimise the network. Origin-destination markets were used as inputs. However, passenger connections and interdependencies between the network planning and flight schedules were not directly modelled. The network changes when considering the temperature changes were limited to 1% of the available seat kilometres flown in a reference profit-based network to guarantee the stability of the solutions. Furthermore, previous studies [14,30] disregarded the impact on the airline network when adopting OIs. OIs, such as ISOs and flying low, increase the flight times and reduce the fleet availability to operate current networks. In addition, passenger connections at hub airports can be compromised by new flight times.

In this paper, we took a step forward by integrating a multi-objective network optimisation model with the previously mentioned OIs to simulate the decision process of a climate-aware airline network and its implications on the flight schedule. The developed framework helps identify the modifications necessary to adopt sustainable network planning and OIs by providing a detailed network model, flight schedule, aircraft rotations, and passengers' itineraries. Eventually, the potential climate impact mitigation is calculated for climate-aware network design and network planning including the OI combination. An extensive range of climate and non-climate key performance indicators (KPIs) are utilised to assess the implications across various scenarios and case studies. The climate KPIs include emissions from the flights (CO_2 and non-CO_2) and ATR values. These KPIs are calculated for the entire network and are further categorised into short-haul and long-haul flights, providing a more comprehensive understanding of the studied OI's impact. Non-climate KPIs consist of monetary and operational performance indicators such as pax, load factor (LF), etc. An iterative approach was adopted to generate the network and flight schedule from scratch. Starting from scratch ensures that the current network and flight schedule characteristics do not influence the final result. The pairwise comparison of the results illustrates how adopting a mitigation strategy can help reduce climate impacts. We also show that the more significant mitigation of climate impact could be achieved by combining OIs. This was captured by comparing the scenarios associated with implementing the OIs with a reference scenario in which no OIs are included.

The primary contributions of the present study are as follows:

1. Developing a multi-objective framework for integrated network planning and a flight schedule adaptable to model the operations of different airline types and considering climate impacts and OIs;
2. Evaluating how climate-aware network design can contribute to climate impact mitigation;
3. Assessing the network effects of adopting the combination of ISO and FL in network planning and its potential contribution to climate impact mitigation;
4. Performing a comprehensive comparison of the results for three airline types, the main hub-and-spoke, the secondary hub-and-spoke, and low-cost carrier. A representative airline per airline type was selected for this study, including KLM, TAP, and EasyJet, respectively.

The remaining part of this paper is structured as follows: first, Section 2 introduces the framework and research methodology. Afterwards, the case studies and associated results are presented in Section 3. Section 4 discusses the results and main conclusions from the case studies. The paper ends with conclusions and recommendations for future research (Section 5).

2. Materials and Methods

This paper presents a framework for assessing airline operations' short-term and long-term climate impact using a multi-objective, multi-agent optimisation that considers the interdependencies of airline network planning and flight scheduling decisions. This framework aims to address the implications of the climate-aware design of airline networks and incorporate a combination of ISO and FL OIs in the network design decisions. The average temperature responses over 20 (ATR20) and 100 years (ATR100) are used to represent aviation's climate impacts. The calculations and associated assumptions are given in Section 2.2. Figure 1 depicts the schematic diagram of the framework.

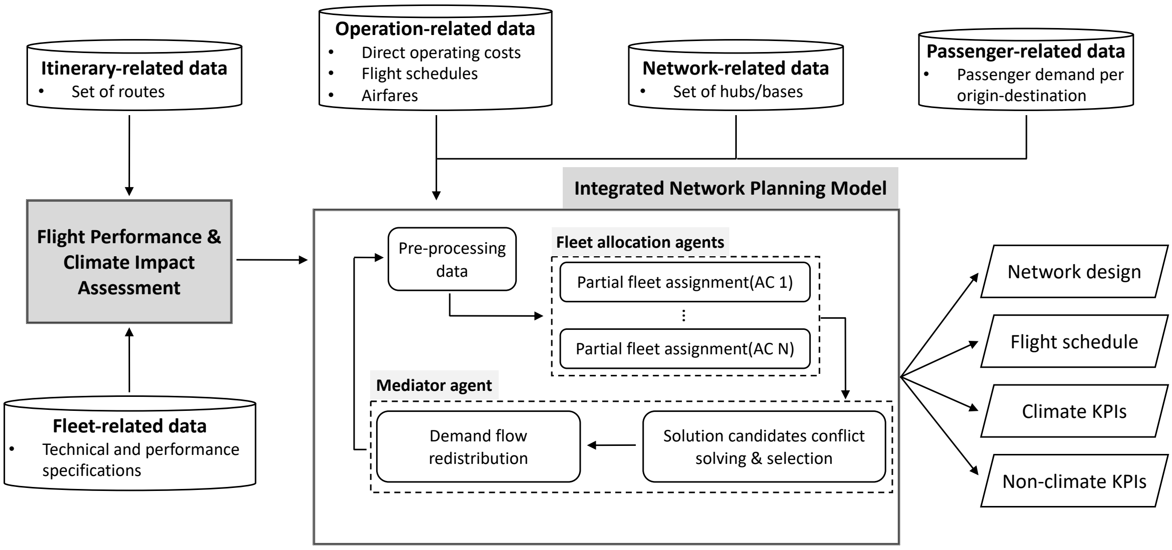


Figure 1. Schematic diagram of the integrated climate-aware network planning framework (abbreviation: AC—aircraft).

The description of the framework components is presented in the following order. Section 2.1 discusses the input data requirements. Section 2.2 gives an overview of the modelling process and fundamental assumption of the climate impact metrics calculations, which delivers the climate-related input. Section 2.3 represents the *integrated network planning model*.

2.1. Input Data

The framework's input data are as follows.

- Itinerary-related data are the set of routes that are operated by the airline.
- Fleet-related data include the technical and performance specifications of all aircraft types in the airline fleet.
- Operation-related data contain a direct operating cost (DOC), the airline's flight schedule and airfares for all the routes in the itinerary-related data.
- Network-related data comprise the hub airport(s) and bases for airlines with hub-and-spoke and point-to-point network structures, respectively.
- Passenger-related data include the average weekly passenger demand for all the airline's origin destinations.

Itinerary- and fleet-related data are used by the *flight performance and climate impact assessment* module to compute the climate-related data for the entire set of routes and the set of route-specific ISO airports. The route-specific ISO airports are based on [20] and delivered through this module. A more detailed overview of the workflow is presented in Section 2.2. Although airlines usually dedicate specific aircraft types to each route (in most cases, only one type), the input data are calculated for all aircraft types in the airline's fleet that can be used in each route.

2.2. Flight Performance and Climate Impact Assessment

The assessment of the required climate and non-climate metrics for the different scenarios is performed in the three following steps: after a definition of the missions to be investigated, including the possible intermediate stop set-up (Section 2.2.1), the flight performance characteristics, as well as the emission quantities, are calculated (Section 2.2.2) before the climate impact assessment is performed (Section 2.2.3). A detailed description of the applied assessment workflow and the underlying modelling chain can be found in Zengerling et al. [20].

2.2.1. Flight Plan Preparation

Based on the given list of ODs as well as the available fleet per operator, an inventory of all possible missions is created. For those flights with a great circle ground distance of more than 2500 nautical miles, a mission interrupted with a refuelling stop is considered in addition to the non-stop connection. The possible intermediate stop airport is selected based on climate-optimising criteria [19,20]. Allowable limits to detour and eccentricity caused by the selected refuelling airport are set to 1.2 and 0.75, respectively, [18]. Restriction to two possible configurations of ISO per route ensures high computational effectiveness by, at the same, incorporating the possible effects from both fuel the efficiency increase and climate-impact reduction through horizontal re-routing and flight altitude changes into the network optimisation.

2.2.2. Flight Performance Assessment and Emissions Calculation

DLR's trajectory calculation module is used for every mission to calculate the required trajectories. Based on BADA4 aircraft performance data, a total energy model approach is applied to calculate the aircraft's state in every simulation step [16,31,32]. This course evaluates the central performance characteristics such as speed, thrust, and fuel flow along the mission.

This is the basis for the following evaluation of emission quantities. While CO_2 and H_2O emissions quantities are directly derived from their proportionate correlation to fuel flow, nitrogen oxides (NO_x) are calculated following the DLR fuel flow correlation method [33]. Hydrocarbon (HC) and carbon monoxide (CO) emissions are assessed with the Boeing fuel flow correlation method [34]. The SO_2 emission index varies regionally according to the local fuel sulphur content [35] and soot emissions are derived with a method by Döpelheuer [36]. ICAO engine emission data bank's information is applied in the aforementioned methods [37].

In the modelling process, the following assumptions are taken:

- An average European flight LF of 0.84 for the selected reference year of 2018 is assumed for every mission [38].
- We exclude both time- and location-specific weather conditions and wind effects as we follow a climatological approach to assess the full reference year's effects.
- On-ground times and emissions are assumed to follow ICAO's landing take-off cycle [37].
- We restrict considered cruise altitudes to either fuel-optimal flight altitudes, including step climbs, or a constant reduced cruise flight level of 31,000 ft. Flight speeds follow the given schedule as per BADA4 data.

This assessment step leads to the fuel consumption, flight time, and emission quantities for CO_2 as well as non-CO_2 emission species used as input in the *integrated network planning model.*

2.2.3. Climate Impact Assessment

The climate impact is assessed in terms of ATR20 and ATR100. We focus our analysis on a future-emission-scenario-based ATR. In contrast to other metrics, this reduces the dependence on the considered time horizon and allows us to take future traffic and technology developments into account [39]. We assume business-as-usual technology developments as defined by Grewe et al. [40]. The climate impact assessment of this study was performed with the nonlinear climate-chemistry response model AirClim [24,41]. It considers changes in the radiative force directly caused by CO_2 and H_2O as well as indirectly induced changes by methane and ozone from NO_x emissions and contrail-induced cirrus in a climatological assessment approach.

ATR results are individually calculated for every possible ISO and non-stop mission from the pre-defined mission inventory. Individual flight results are based on mission-specific emissions gridding. This assessment step leads to the optimisation metrics of ATR20 and ATR100 per flight and scenario.

2.3. Integrated Network Planning Model

Airline network planning involves designing the network structure commonly aimed at maximum profitability. The network is defined by computing the frequencies per route. The frequencies should be computed according to the availability of resources and the possible allocation of fleets to the network. To address these inter-dependencies, we developed an *integrated network planning model* in which network design is combined with fleet allocation decisions. The result is a flight schedule presenting the flight times and respective frequencies per route and the aircraft routes to be followed to provide flight capacity.

The *integrated network planning model* uses a multi-agent approach to solve a multi-fleet and multi-objective network optimisation problem. The problem is solved for a representative week for a given season, in which the average passenger demand in all ODs is considered. It was also assumed that the resulting network structure and flight schedule would be in place for the entire season. Each fleet type was assigned, in parallel, through a fleet allocation agent to promote the concurrency of calculations. Moreover, the climate impact associated with the route selection decisions was incorporated into the network planning objective function of the agents. Agents use a dynamic programming algorithm to solve their problems.

The airline network was represented as a time–space network [42]. The optimal aircraft assignment to that network was determined after the mediator agent compares the solutions of the different fleet allocation agents provided. The coupled time–space network and iterative fleet allocation approach offer the opportunity to simultaneously solve network planning and flight scheduling problems and capture the interdependencies in the final solution. This integrated approach also helps improve the run time. The final result delivered by the framework includes the network design, flight schedule, aircraft routes, and a set of climate and non-climate KPIs to facilitate an in-depth evaluation of output.

More detailed information on the pre-processing data utilised by the model framework, the functions performed by the fleet allocation agents, and the purpose of the mediator agent is provided in the subsequent subsections.

2.3.1. Pre-Processing Data

The set of served ODs per season and their associated average weekly demand can be derived from itinerary- and passenger-related data. In addition, demand distribution on the travelling demand is required throughout the days and hours of the week to develop the flight schedule. To tackle the complexity involved in the passenger preference modelling, it was assumed that most of the passengers are willing to travel at the time that flights are currently provided. Based on this assumption, the passenger demand was modelled as an accumulated distribution near the actual flight time.

Given the actual departure times, the demand distribution associated with each flight was assumed to follow a normal distribution with a 2 h standard deviation. Its mean value equals the departure time for that flight. Aggregating demand distributions for all flights operated by an airline in a route results in the weekly demand distribution function for that route. *Passenger demand distribution* is a demand distribution function in which the summation of demand distribution values for all the time steps in a week is equal to the weekly average number of passengers the airline serves. In this approach, standard deviation represents the passengers' willingness to change their flight departure time within an interval of the departure time. Figure 2a depicts the weekly *Passenger demand distribution* for KLM's AMS–ATL route in 2018.

It was also assumed that each flight being scheduled would be taken by passengers available within a maximum of a 4 h interval of the scheduled flight (2 h on each side), which is shown with a dashed line in Figure 2b. This interval is called the *attraction band* and is an input parameter of the framework. *Passenger flow* is a part of passenger demand captured within the *attraction band* and constrained by the capacity of the aircraft when analysing each aircraft type. In the pre-processing stage, *passenger flow* is calculated for all aircraft types available per time step in the model and passed on to the fleet allocation agents to calculate the flight revenue and profit. Along with *passenger flow* input, airfares, DOC, flight time, and climate impact (ATR20) are provided to fleet allocation agents. DOC and ATR20 are calculated according to all aircraft types that can operate in the routes and are assumed to be fixed during the season. Calculating the input for all possible aircraft types results in diverse potential solutions and significantly improves the profit and climate impact objectives in the partial fleet assignment problem solutions.

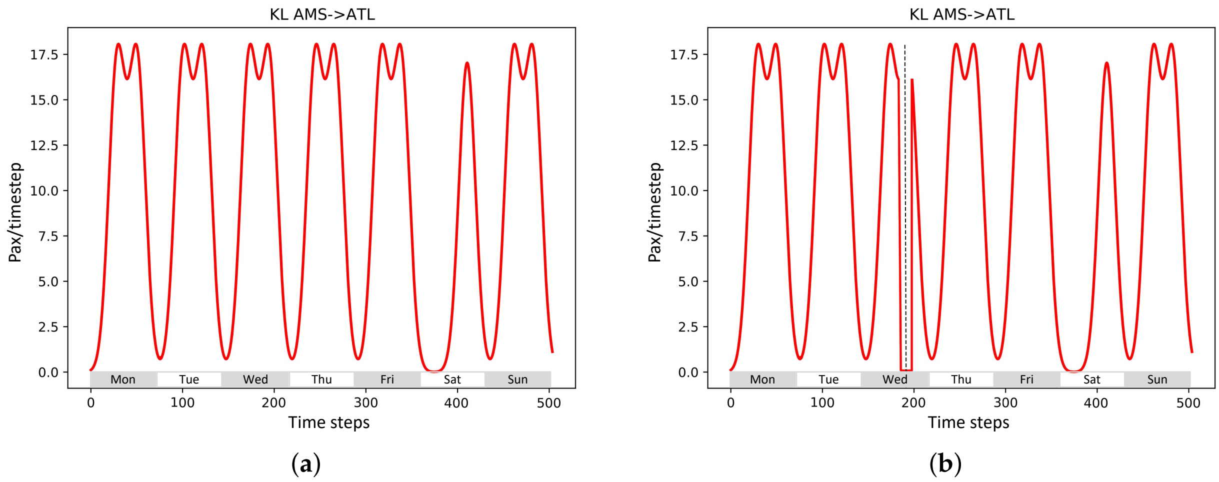


Figure 2. Weekly passenger demand distributions for KLM in 2018 (each time step equals 20 min): (**a**) initial demand; and (**b**) updated demand after assigning a flight.

2.3.2. Fleet Allocation Agents

The fleet allocation agents define the best weekly flight schedule and aircraft routes per aircraft type in the fleet. A number of agents, equal to the number of fleet types, solve the partial fleet assignment problem. All the agents receive the same input but solve the fleet assignment problem partially, which is only associated with the available fleet from their own aircraft type. The problem that fleet allocation agents address has a similar approach to the framework in [43,44]. At the same time, it was improved to incorporate the OIs-related considerations and multi-objective formulation. The idea is to break down the optimisation problem into smaller sub-problems for each aircraft type. Each fleet allocation agent determines their aircraft type's best route and schedule. They solve the problem independently and define the optimal allocation according to the considered route, *passenger flow* per time step, associated airfare, and operating costs.

Under standard circumstances, the optimal aircraft assignment is solely determined by profit (i.e., the difference between the potential revenue from passenger transportation and the operating costs of the flights on the schedule). However, if the climate impact is taken into account as an additional planning objective, the objective function formulation needs to be adjusted. To achieve this, we used a modified profitability metric [45], which factors in profit per climate impact unit (ATR20). The goal then becomes to identify the network planning decisions that maximise the ratio of profit to ATR20 values. We introduced ATR20 into the objective function using the formulation presented in Equation (1). Using ATR20 as the climate impact unit in this equation was due to focusing on the climate impact in the near future. Therefore, using any other unit in this regard, including ATR100, is possible and only depends on the research goal.

$$
\begin{aligned}
T_i^t &= \frac{Profit_i^t}{ATR20_i} && if Profit_i^t \geq 0 \\
T_i^t &= \frac{Profit_i^t}{ATR20_{max} + ATR20_{min} - ATR20_i} && if Profit_i^t < 0
\end{aligned}
\tag{1}
$$

The multi-objective approach utilises the T_i^t formulation, which stands for *transformed profit*, where i is the route index and t is the time step. Different formulations are used to distinguish the positive and negative profit values to keep this metric monotonically increasing with the increase in profit and decrease in ATR20. Increasing a positive profit in the numerator or decreasing ATR20 in the denominator results in a higher value for *transformed profit*. In the case of negative profits, a lower ATR20 results in a higher absolute value of the *transformed profit*. Nevertheless, it is worse when maximising the objective function due to the negative sign.

The time–space network represents the possible movements of aircraft over time (as can be seen in Figure 3). The arrows indicate the aircraft flights in time t (vertical axis) and space i (horizontal axis, representing airports). The edges represent the possibility of flying between airports at a specific departure time or the decision to ground the aircraft at the airport. The problem of determining which flight arcs the aircraft should be allocated is solved using a dynamic programming algorithm. According to this algorithm, the potential profits per flight are mapped, and the optimal aircraft route and flight schedule are obtained following the shortest path algorithm (i.e., profit maximisation). The profit per flight is calculated by multiplying the estimated *passenger flow* by the average airfare on that route deducted by the associated DOC.

The agents sequentially follow this process to allocate a set of aircraft of the same type to the network. The number of aircraft to allocate per agent is an input parameter constrained by the number of aircraft available from that fleet type. Between aircraft allocations, the demand per origin and destination pairs are updated. The *Passenger flow* is subtracted from the *Passenger demand distribution* (as can be seen in Figure 2b). Regarding hub-and-spoke airlines, particular attention is given to transferring passengers at the hub airport(s). Given the focus of hub-and-spoke airlines on providing a good connection between the flights and consolidating passengers at the hub, priority is given to these passengers when deciding which passenger to take on each flight departing to or from the hub airport(s). If connecting passengers cannot make it from their origin to their destination with the incumbent flight schedule, they are made available at the hub airport to be transported to their destination when adding subsequent aircraft to the schedule. This way, the agents create waves of flights at the hub airport to consolidate the connecting demand and create the opportunity to generate more flights. After running all the fleet allocation agents, this process results in a set of aircraft routes and flight schedules per aircraft type. These schedules are then passed to the mediator agent to select the final solution.

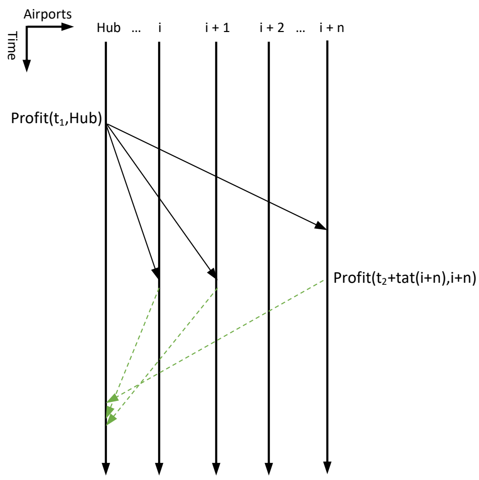


Figure 3. Time and space network—*profit(t,i)* matrix contains the achievable profit values associated with being in an airport i at the time step t. The matrix is calculated during the solving of sub-problems in the dynamic programming approach. The green arrows indicate the best next possible flight given the previous flight (abbreviation: tat—turnaround time).

2.3.3. Mediator Agent

The mediator agent compares the objective value of the multiple fleet allocation agents' schedules to determine the best schedules while avoiding conflict between schedules. A conflict is defined as assigning more than one aircraft to a similar time step and route. The mediator agent solves the conflicts by eliminating the flights which cause conflict from the solution candidates set. Solution elimination while solving conflicts is based on the objective value of the solutions. This approach guarantees that an entire solution set is not eliminated due to the conflict in a few flights. The minimum number of candidates chosen in each iteration is the same as the number of aircraft assigned by fleet allocation agents. The next step for the mediator agent is to redistribute the demand flows composed of the set of schedules selected to date. The incumbent flight schedule is examined during the redistribution process to avoid having flights with an extremely low LF. Furthermore, connecting passengers are rearranged, considering the possible connections and local passengers to ensure that no connecting passenger remains at the hub by the last iteration.

The resulting incumbent flight schedule and passenger flows are considered in the pre-processing data block to recompute the demand left for the following iteration. This iterative process is repeated until no more aircraft are available in the fleet, the aircraft utilisation associated with the schedules does not respect a minimum weekly aircraft utilisation, or the objective value of the candidate schedules does not meet a threshold (e.g., the added flights have to result in a higher profit than zero).

3. Results

The framework described above was used to conduct a pairwise scenario comparison analysis to investigate the potential climate-aware network planning and climate mitigation impact of ISO and FL implementation. In addition, a detailed evaluation of climate and non-climate KPIs was introduced to reveal the implications of the scenarios in comparison to the reference case. The calculations were performed for each season to ensure that changes in operational boundary conditions were considered. Finally, the yearly average values for the KPIs were reported to provide an overview of the performance in all scenarios and case studies.

3.1. Scenarios

Four scenarios were investigated using the integrated modelling approach in airline network planning in conjunction with the network-related OIs. The scenarios are summarised in Table 1. The first scenario, namely the business-as-usual (BAU) scenario, was considered the reference scenario, representing what is assumed to be the common airline network planning strategy. The objective is to maximise profit while following the great circle trajectories at fuel-optimal altitude. No OIs are considered in this reference scenario.

Table 1. Scenario descriptions.

Scenario	Objective	Flight Level	Case Study Airlines
BAU	Profit	Fuel optimal	KLM, TAP, EasyJet
ATR	Profit/ATR20	Fuel optimal	KLM, TAP, EasyJet
ATRISO	Profit/ATR20	Fuel optimal	KLM, TAP
ATRLISO	Profit/ATR20	31,000 ft.	KLM, TAP

Three other scenarios represent multi-objective network planning and two ISO-related OIs, respectively. These scenarios were designed to capture the framework's capabilities and the synergy gained by incorporating OIs into the network planning problem. The second scenario (ATR) follows similar conditions to the BAU scenario, but in this case, the ATR20 associated with each route was incorporated using the transformed objective function (Equation (1)). The new objective function ensures that the resulting network has the highest profit-to-ATR20 ratio. This scenario is called ATR after its altered objective function.

The last two scenarios (ATRISO and ATRLISO) also optimise the network using the same objective function but consider the option of ISO in some of the long-distance routes for which a feasible stop-over airport is available. A minimum range threshold of 2500 nautical miles was used when defining which routes could be considered for ISO. The ISO option was considered an alternative to a direct flight in all the ISO routes. Therefore, the solutions for these scenarios may include both direct and ISO flights for the same route, depending on the aircraft type allocated to the flight, flight time, associated costs, and ATR impact. The difference between these two last scenarios is that the maximum flight altitude for the ISO flights in the last scenario (ATRLISO) was considered to be 31,000 ft, lower than what is usually the fuel-optimal flight altitude. This represents a trade-off between the flight cost efficiency and climate impact.

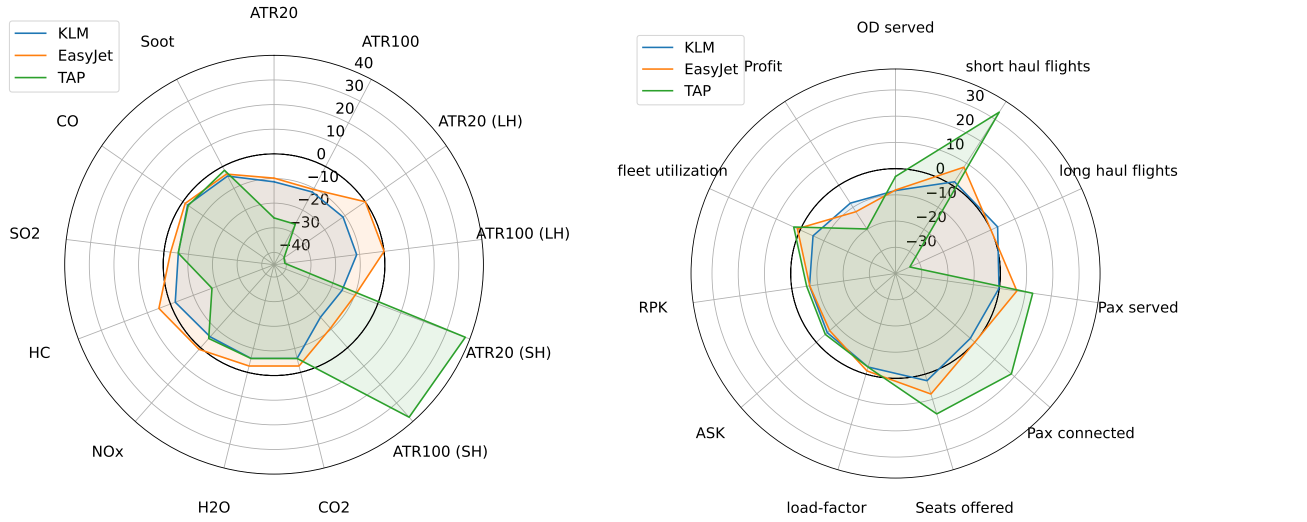
These scenarios were analysed for three European airlines representing different operation types: KLM, one main-hub-and-spoke; TAP, one smaller multi-hub airline; and EasyJet, a point-to-point low-cost carrier. Since EasyJet had no flights exceeding the ISO's minimum range threshold, it was not considered in the last two scenarios. The overall modelling framework is the same for all three airline types in this study. The only difference is the network structure and routing constraints. Flights on hub-and-spoke airlines are only to or from the hub. Passengers on connecting flights are transported to the hub, where they wait for the next flight to their destination. In comparison, multi-hub airlines have a variety of operational strategies. TAP operates two main hubs with frequent flights connecting the hubs throughout the day. Almost the same policy for connecting passengers applies here. The difference is that some of them must catch an additional connecting flight between hubs because their final flight leg departs from the other hub. Lastly, low-cost carriers mainly operate a point-to-point network where connecting passengers is not the primary concern.

When analysing the results for the scenarios, we considered climate and non-climate KPIs. For the climate KPIs, we considered ATR20, ATR100, CO_2, H_20, NO_x, HC, SO_2, CO, and Soot. For the non-climate KPIs, we computed the profit, number of routes served, the number of flights in the network, the amount of direct and connecting passengers served, the average LF of the network, the number of seats offered, the available-seat kilometres (ASK), the revenue-passenger kilometres (RPK), and the fleet utilisation measured in hours of flight. We decided to split the analysis of the ATR values and the number of flights into short-haul and long-haul flights to compare the impact at different scales in the network. To do this, we used 2500 nautical miles as the threshold to distinguish long-haul from short-haul flights.

Passenger itineraries, passenger demand, flight schedule data, and airfares were extracted from the Sabre market intelligence database [46]. To avoid pandemic effects on flight operations and demand, we used 2018 data. The yearly data were divided into low season (S-low) and high season (S-high). The DOC was inferred from multiple datasets, including FAA [47].

3.2. ATR Scenario

In this analysis, we compared ATR with BAU scenarios for all three airlines to show how considering climate impact would affect an airline's network structure. The aggregated implications of the new objective function on the climate and non-climate KPIs are depicted in Figure 4. According to the findings, EasyJet and KLM may reduce around 11% of their ATR20 and ATR100 while compromising 10% of their profit. Because there is no long-haul flight in the EasyJet case study, the KPIs associated with long-haul flights remain unchanged for this airline. TAP, on the other hand, reduces ATR20 by 36% while losing 20% of its profit. TAP has a relatively higher ATR20 reduction because the long-haul flights are significantly reduced in the new network plan. TAP has fewer long-haul destinations than KLM, resulting in limited alternative long-haul destinations when aiming for ATR20 reduction. As a result, some of the widebodies are assigned to shorter distances, significantly reducing long-haul ATR20 at the cost of increasing short-haul ATR20. In general, long-haul flights are more profitable than shorter ones. Therefore, reducing the number of long-haul flights may deteriorate the profit more than tweaking the short-haul routes. Figure 4b depicts this scenario's increase in short-haul flights. Despite a high percentage increase in the ATR20(SH) value, the net ATR20 shows a reduction.



(**a**) (**b**)

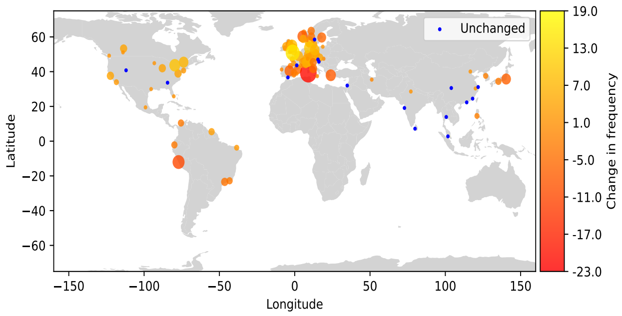
Figure 4. Average annual changes of the KPIs for ATR compared to BAU (abbreviation: LH—long-haul; SH—short-haul): (**a**) assessment of the climate KPIs (%); and (**b**) assessment of the non-climate KPIs (%).

The relative changes in the number of both short- and long-haul flights show an increase for KLM. KLM also offers more seats due to the increased number of flights. At the same time, ASK decreases, which is due to the fact that flights are being operated on shorter long-haul routes. RPK is also reduced because shorter long-haul flights are not as profitable as the longer ones. Therefore, there is a shift from flying in longer long-haul routes towards shorter ones. Shorter flights also result in lower utilisation because, on average, an aircraft spends more time in terms of turnaround time and waiting for the next flight rather than flying in a route with a long block hour. KLM serves a similar number of passengers in this scenario, but the portion of connecting passengers is lower than in the BAU scenario which contributes to the lower profit. Transporting connecting passengers is more profitable because of the average higher airfare as well as improving the LF of the outbound flights from the hub airport.

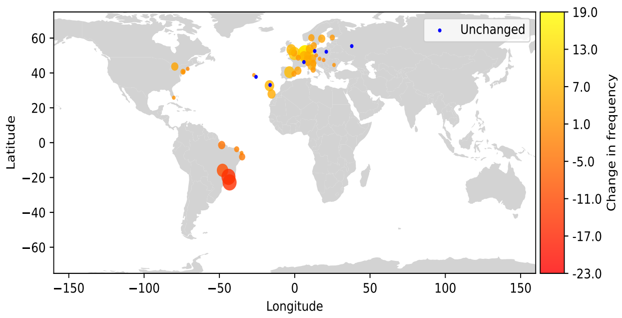
In the TAP and EasyJet case studies, similar patterns of relative changes in non-climate KPIs occur. The total number of flights and offered seats are increased while the ASK and RPK are decreased. In contrast to KLM, fleet utilisation increases for TAP and EasyJet. An increase in fleet utilisation is expected to lead to more profit, but in this study, this was not the case. TAP and EasyJet reduce their flights in their highly profitable routes due to the high ATR20 value at the same time. Consequently, the extra profit gained by increasing fleet utilisation compensates for a part of the profit loss from fewer flights on highly profitable routes.

Further examination of the TAP and KLM networks reveals a strong relationship between the viability of long-haul flights and the effectiveness of feeding flights. In order to maintain profitable long-haul flights in the network, enough connecting passengers must be transported to the hub at the right time. Long-haul flights are only scheduled if a break-even LF is met. In particular, for TAP, it is difficult to keep the frequency of some long-haul routes, even for some high-yield routes. Although the number of short-haul flights is increased, the required connecting interval at the hub airport is not met. Hence, the majority of extra passengers in the ATR scenario are local passengers who do not contribute to the profitability of the outbound connecting flights. In the case of KLM, the demand is more flexible (due to the availability of a larger number of destinations) so many alternative feeding flights could be scheduled. There are also, in several cases, enough local passengers to overcome the scarcity of connecting passengers. In this sense, the outbound flights have a greater chance of reaching the break-even LF regardless of how many connecting passengers are transported to the hub.

The weekly frequency difference of all routes in the ATR and BAU scenarios was compared to investigate the implications of ATR on the network structure. Figure 5 shows the results for S-low, while Figure A1 shows the same result for S-high. In the KLM network, the spoke airports closest to the EU's southern and northern borders show the most significant reduction in weekly frequency. At the same time, the destinations in the EU centre draw the fleet's spare time when they were not flying to their destinations in the BAU scenario. The results show that an aircraft is encouraged to fly shorter distances by introducing the ATR scenario. In the TAP case study, flights to destinations in Brazil are reduced due to their climate impact and lack of proper feeding flights. The EasyJet network follows a similar pattern. To reduce the total ATR20, longer short-haul flights are being replaced with shorter-distance flights. As shown in Figure 5c, EasyJet's unchanged destinations are significantly higher. This is due to the fact that EasyJet has an almost homogenous fleet, and ODs are not very different in terms of distance and location. Thus, few alternatives can outperform the solutions in the BAU scenario.



(**a**)



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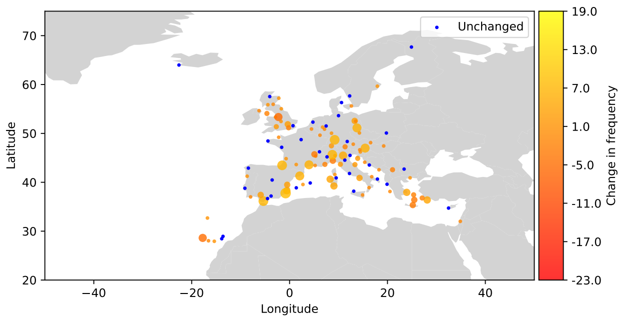
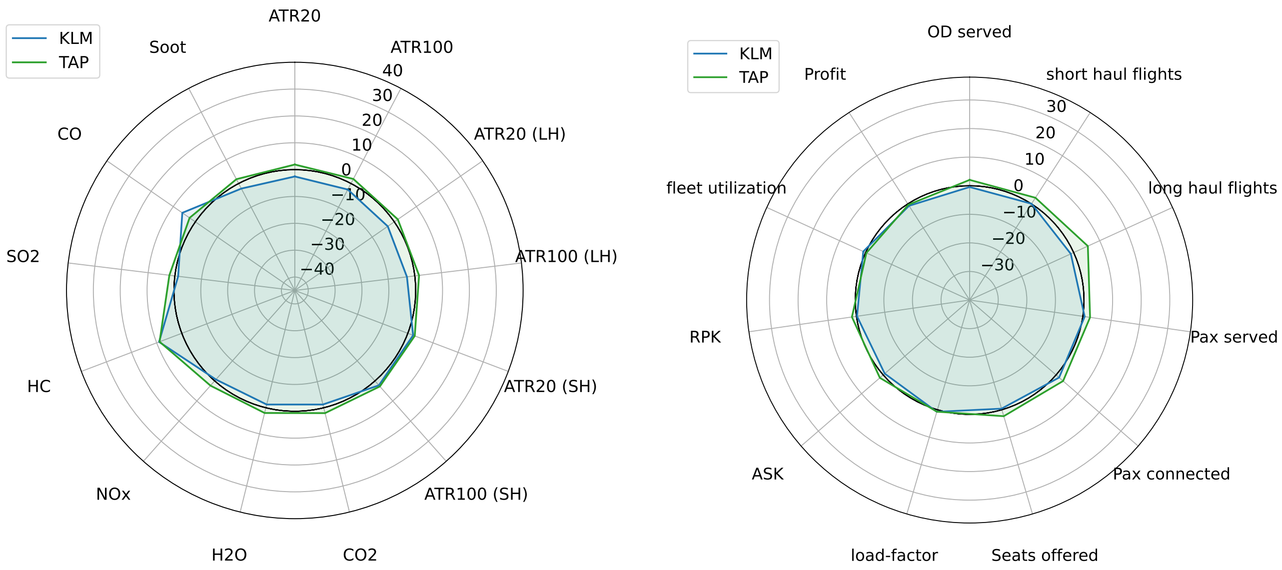


(**c**)

Figure 5. Weekly frequency changes of representative airlines for ATR compared to the BAU scenario—S-low: (**a**) weekly frequency changes of the routes in the network—KLM; (**b**) weekly frequency changes of the routes in the network—TAP; and (**c**) Weekly frequency changes of the routes in the network—EasyJet.

3.3. ATRISO Scenario

Besides incorporating the ATR20 in the objective function, ISO operation is also considered in this scenario. The same set of KPIs is used in this case, and only the KLM and TAP networks are considered. The pair-wise comparison was implemented for ATRISO versus ATR. The yearly aggregated results are presented in Figure 6.



(**a**) (**b**)

Figure 6. Average annual changes in the KPIs for ATRISO compared to ATR: (**a**) assessment of the climate KPIs (%); (**b**) assessment of the non-climate KPIs (%).

This case study reveals that ISO implementation can provide environmental and operational benefits to airlines. For KLM, operating ISOs causes the network's total ATR20 and ATR100 to be decreased, as depicted in Figure 6. Moreover, ISOs can help airlines expand their network and serve more ODs without adding more aircraft. KLM has a 5% reduction in ATR20 with no significant profit changes compared to the ATR scenario. However, additional take-offs and landings cause a 5–10% increase in HC and CO. Conversely, the TAP study shows a slight increase in ATR20 and ATR100 after incorporating ISO OIs into its network planning process. The observed rise is not directly due to implementing ISOs, but rather a network expansion, resulting in more flights, passengers, and ODs served, as presented in Figure 6b. While a higher number of flights would increase ATR20, ISO OI helps to mitigate most of the effect. Similarly to KLM, TAP experiences a peak in CO and HC due to ISO implementation. The most frequently used ISO airports are GUU, TOF, and BXR for the KLM and CVU and MVF for the TAP case study. A list of candidate ISO airports which are more frequently visited on a weekly basis is reported in Tables A1 and A2 for representative airlines.

In the TAP case study, the similar relative increase amount in the pax served, pax connected, and seats offered suggests that the extra capacity which is provided at the network level by introducing the ISO flights is almost fully used to transport additional passengers. The increase in the RPK also shows that ISO flights can improve the revenue at the network level as the narrowbodies could operate on a route which was only possible using a widebody.

Based on the results shown in Tables 2 and 3, it appears that the total percentage of ISO-adopted routes is constrained by the extra DOC associated with it. Our analysis indicates that ISO flights are more frequently scheduled in S-high than in S-Low due to the higher average airfares during the former season. Additionally, we found that implementing ISO using a narrowbody aircraft is more likely to be feasible from a DOC perspective than with a widebody aircraft, as the additional cost is significantly lower. In the other words, constraints at the network level determine where and when an ISO would be feasible and significantly affect the implementation results.

Table 2. Weekly flight type composition and relative changes in climate and profit KPIs—KLM.

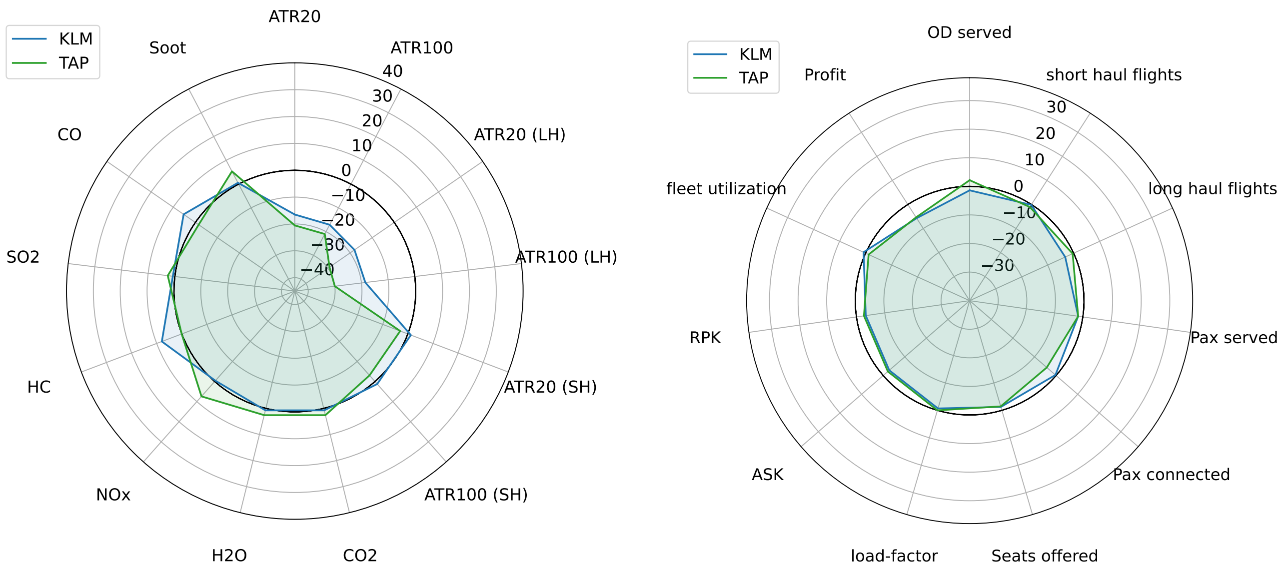
Scenarios	# Direct Flights		# ISO Flights		Δ ATR20 (%)		Δ ATR100 (%)		Δ Profit (%)	
	S-Low	S-High	S-Low	S-High	S-Low	S-High	S-Low	S-High	S-Low	S-High
BAU	2322	2334								
ATR	2368	2376			−11	−12	−11	−12	−10	−6
ATRISO	2256	2170	104	204	−13	−14	−14	−14	−11	−6
ATRLISO	2077	2020	271	334	−44	−28	−26	−29	−16	−10

Table 3. Weekly flight type composition and relative changes in climate and profit KPIs—TAP.

Scenarios	# Direct Flights		# ISO Flights		Δ ATR20 (%)		Δ ATR100 (%)		Δ Profit (%)	
	S-Low	S-High	S-Low	S-High	S-Low	S-High	S-Low	S-High	S-Low	S-High
BAU	1062	1136								
ATR	1232	1286			−24	−28	−25	−28	−23	−17
ATRISO	1290	1092	4	10	−22	−27	−24	−28	−20	−20
ATRLISO	1104	1182	112	96	−43	−40	−44	−40	−25	−23

3.4. ATRLISO Scenario

The final comparison made between the lower-altitude ISO (LISO) and the ATR scenario is illustrated in Figure 7. Our analysis reveals that LISO is more effective than ISO in reducing the network's climate impact for both KLM and TAP, with potential reductions of 18% and 21% in ATR20, respectively. However, flying at a lower altitude for LISO OIs would require more fuel, resulting in a higher DOC. Furthermore, most emission types are slightly increased due to deviations from the optimal fuel altitude and increased fuel consumption. The profit loss for both airlines is approximately 6%, and most of the reduction in ATR20 is attributed to decreasing the long-haul ATR20. Overall, the combined use of ISO and FL shows promising results in mitigating the network's climate impact.



(**a**) (**b**)

Figure 7. Average annual changes of the KPIs for ATRLISO compared to the ATR scenario: (**a**) the assessment of the climate KPIs (%); and (**b**) assessment of the non-climate KPIs (%).

The introduction of FL seems to increase the added value of ISOs. There are more ISO flights in the LISO results, and all the airports which are used in the ISO scenario are also used in the LISO scenario. There is also no proportional relationship between the number of ODs associated with a candidate ISO airport and the number of times it is visited per week. The ISO alternative would be selected based on the profit margin of the route and network-related constraints. Therefore, an airport located at the perfect spatial point will not necessarily be frequently visited for ISO flights.

The flight type composition and the associated climate impact reduction compared to BAU for all the scenarios are reported in Tables 2 and 3. The ATR scenario has more flights than the BAU scenario because closer destinations are served, resulting in shorter flight times. Thus, the weekly schedule of an aircraft could accommodate more flights, which increases the total number of flights per week, and the optimisation subroutine could not find a significantly better solution than what we have in the ATR scenario for the TAP case study. As a result, we see a relatively close objective function value for both scenarios, even though the network structure and the number of flights differ. Additionally, however, the number of ISO landings is lower in ISO, and all the airports which are used to implement LISO are also used in the ISO scenario.

4. Discussion

We developed a multi-objective integrated network planning framework that can incorporate the climate impact and the commonly used profit in its objective function. ISO and FL OIs are also merged and were assessed by the developed framework to find the potential gains of considering them in the network planning phase. Four scenarios were investigated using the proposed framework. The BAU was assumed to represent the current airlines' situation and assumed to be the reference case for pairwise analysis. Profit is the only objective in the BAU scenario. In contrast, a transformed objective function was used in all other three scenarios to simulate the network decision-making process when the climate impact was also considered.

We neglected the impact on passenger demand and prices in these studies and considered that the climate impact and profit have equal weights in the transformed objective function. The climate impact of a flight depends on the emission compounds, the location, and multiple other climatological parameters such as temperature, etc. As the proposed framework was developed to serve strategic studies, the climate impact was calculated using great cycle trajectories and the average climatological parameters.

We conducted a comparison of our findings with the existing literature in Table 4, focusing on three key indicators: financial implications (profit loss), climate change mitigation (ATR100), and route efficiency (LF). Overall, we found that previous studies tend to overestimate the impact of the OIs. This discrepancy arises from the influence of network effects on the outcomes of adopting different OIs. Specifically, airlines face limitations in terms of the number of aircraft available for allocation within their network to exploit the benefits of these OIs while still efficiently meeting the overall demand. They must consider daily and weekly demand patterns and ensure smooth passenger connections at hub airports. These factors result in cascading effects on multiple routes, limiting the potential benefits of adopting the OIs.

Furthermore, some of the OIs involve additional flight times and DOC, which can affect the feasibility of implementing these OIs on certain routes within the network. Our results reveal that, in several routes, the OIs are only adopted for a portion of the flights operating on those routes. The ISO and FL options are typically used when the fleet is available to fly for longer durations without compromising connection waves at the hubs. However, when such conditions are not feasible, the optimal flight decision is to choose the non-stop flight option at the standard altitude and speed.

In summary, our analysis underscores the importance of considering network effects and operational constraints when evaluating the potential impact of OIs. These factors influence the adoption of OIs on specific routes, and the optimal flight decision depends on the availability of the fleet and the need to maintain smooth connections at hub airports.

Table 4. Comparison between the absolute results compared to the business-as-usual case obtained in the literature and the average annual results for each of the three scenarios in this study (KLM). * This study did not include the ISO OIs and only considered FL.

Criteria	ATR Scenario		ATRISO Scenario		ATRLISO Scenario	
	[30]	This Study	[20]	This Study	[15] *	This Study
Profit loss	Up to 12%	10%	-	10.5%	-	14%
Climate impact mitigation (ATR100)	up to 12.5%	11%	Up to 40%	15%	up to 21%	17%
LF	Up to −30%	−3%	-	−2%	-	−4%

The airline network level comparison between the ATR and BAU scenarios revealed a trade-off between profitability and climate impact. Long-haul flights are more profitable but also have a significantly higher climate impact. The ATR scenario showed that allocating aircraft to shorter routes was a common pattern for all three airlines to mitigate their climate impact. Although short-haul flight schedules were greatly impacted, long-haul flights experienced minimal changes in schedule and frequency. Not all long-haul flights saw a decrease in weekly frequency; the fleet was reallocated to other routes to maintain the average fleet utilisation and profit. If sufficient demand exists, some of the most profitable long-haul flights attract part of this unused aircraft capacity.

Another option to avoid grounding the long-haul fleet in the ATR scenario is to serve medium-haul destinations. The findings suggest adopting new network design objectives or operational concepts may require re-evaluating the fleet composition from a fleet management perspective. In the KLM case study, the fleet allocation to the new network was found to be less efficient than the reference one, resulting in a relative drop in average fleet utilisation compared to other airlines. Airlines may need to make appropriate short- or long-term fleet management decisions to address the potential inefficiencies due to climate-aware network planning. These changes may cause the flight LF to deviate from the assumed average European values used for DOC and climate impact calculation. Therefore, in the ATR scenario, the reduced LF, compared to the BAU scenario, can further help mitigate climate impact and costs.

We used the proposed framework to provide an overview of the actual network-level consequences of implementing the ISO and FL. We presented the results by comparing an OI-specific scenario with the ATR scenario. We discovered that ISO could help decrease the total ATR20 and expand the network (serve more destinations). According to the case studies, lowering the climate impact and network expansion ISO contributions may not coincide due to the fact that they have contracting effects in ATR20. This also may not be possible to be anticipated what would be the ultimate effect as it is highly case-dependent. We also observed that 4–7% of the flights adopted a weekly ISO operation, and the portion of ISO flights in S-high is more than it is in S-low. Further analysis showed that the average airfare in S-high is about 30% and 44% higher for TAP and KLM, respectively. Therefore, this season has a larger profit margin for both airlines, which allowed more ISO to be implemented. The additional cost of ISO is a noticeable impediment towards widely implementing it. In the case studies, extra landing and take-off in ISO resulted in increased CO and HC emissions by up to 10%. Considering the additional DOC, ISO may not be a realistic choice for all network routes for an airline. Nonetheless, it can provide additional flexibility in network planning while using the same fleet composition.

On the other hand, LISO could produce a significant ATR20 reduction when combined with the network planning model. The increase in the DOC for LISO is slightly higher than ISO as the cruise altitude shifts from the optimal fuel altitude. At the same time, the reduction in the ATR20 is high enough to make LISO a better option than ISO. LISO emits non-CO_2 emissions at an altitude at which atmospheric reactions result in a lower ATR20, and it helps reduce the ATR20 between 17 and 31% at the network level in our case studies. Most of the ATR20 reduction in this scenario was gained by modifying the long-haul route in both TAP and KLM. It can be concluded that a revision in planning long-haul routes should be the main focus of network climate-friendly planning revisions. Long-haul flight changes may necessitate changes to short-haul flights to maintain the connecting passenger flow at hub airport(s).

Integrating ISO and LISO into airline network planning requires a careful consideration in terms of network design and flight schedules. While previous studies have assumed ISO or FL for a limited number of flights exceeding a specific duration in a specific region, our research demonstrates that such assumptions may not be practical in practice. Incorporating these operational improvements necessitates various adjustments, subject to network structure and constraints. As such, the mitigation potential gained according to the ISO is reported at around 40% in the literature [19,20]; if we look at our result for the same type of routes, we see that it is not more than 28% for TAP and 14% for the KLM case studies. The difference is due to the network effects and practical implementation conditions associated with each airline type that are taken into account in the case studies.

Moreover, integrating ISO and LISO into airline operations affects airlines and other aviation stakeholders, such as ISO-candidate airports, air traffic control, and passengers. For instance, additional landing and take-off in ISO operations increase the workload of air traffic controllers, while longer travel times may decrease the passenger acceptance of ISO flights. Furthermore, the added landing can also impact the safety margin which highlights the need for a thorough evaluation of the implications of integrating ISO and LISO in airline operations.

5. Conclusions and Outlook

In this study, we developed a framework for multi-objective airline network planning. We assessed four scenarios using the framework to evaluate the synergy between climate-aware network design and OI integration. We adopted an integrated approach to simultaneously solve network planning and flight scheduling to address the involved interdependencies. For the first time, the ISO and LISO implementation was evaluated at the network level to capture the implications and network effects associated with them. We also performed a comprehensive comparison of the results for three representative airline types. The comparison showed how a climate-aware network design in combination with OIs can assist in climate impact mitigation. Such an advancement offers great potential to enhance the effectiveness of network planning and decision-making processes in the aviation industry, leading to more efficient and sustainable operations.

To mimic the profit-maximising nature of airlines, a BAU scenario with a profit-only objective function was used as the reference case. This scenario is based on the actual demand distribution from the operations of the representative airlines in 2018. ATR20 was assumed as the climate impact representative, and incorporating it into the optimisation subroutine was aided by a transformation function. The evaluated case studies suggest that the ATR scenario can reduce the climate impact by 10–36% at the cost of 8–20% profit loss. LISO also outperforms the ATR scenario regarding the ATR20 reduction. The ATR20 reduction in LISO could be up to 31% more than the ATR scenario, while the profit is reduced by only 6%. The climate impact mitigation values show a lower total reduction than similar studies due to the network implications of implementing the OIs.

We assumed that passenger demand and airfares are static, and are not affected by changing operational conditions. To improve the reliability of the results, it would be interesting to incorporate the relationship between air service, costs, and competition in future work in both demand and airfares. Furthermore, uncertainties in the flight's climate impact calculations need to be addressed in more detail. Incorporating the uncertainty modelling of climate impact is necessary to obtain more accurate results.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AC	Aircraft
ATR	Average temperature response
ATR100	Average temperature response over 100
ATR20	Average temperature response over 20
ATRISO	Network optimisation scenario with profit & ATR objectives including ISO
ATRLISO	Network optimisation scenario with profit & ATR objectives including LISO
BAU	Business as usual
DOC	Direct operating cost
FL	Flying lower
HC	Hydrocarbons
ISO	Intermediate stop-over
KPI	Key performance indicator
LH	Long-haul
LISO	Lower intermediate stop-over
OI	Operational improvements
SH	Short-haul
S-low	Low season
S-high	High season
UNFCCC	United Nations Framework Convention on Climate Change

Appendix A. ISO Flights and Airport List

Table A1. Candidate intermediate stop-over airports for KLM network.

ISO Airport	ODs	Times Visited (LISO) (Week)	ISO	LISO
ALB	MEX–AMS, AMS–MEX	2	×	×
BXR	HKG–AMS, CTU–AMS, CGK–AMS, AMS–HKG	15	×	×
CND	BOM–AMS, AMS–BOM	12	×	×
FEN	GIG–AMS, AMS–GIG	8	×	×
FNC	AMS–FOR, FOR–AMS	7		×
GJR	AMS–YVR, YVR–AMS	13	×	×

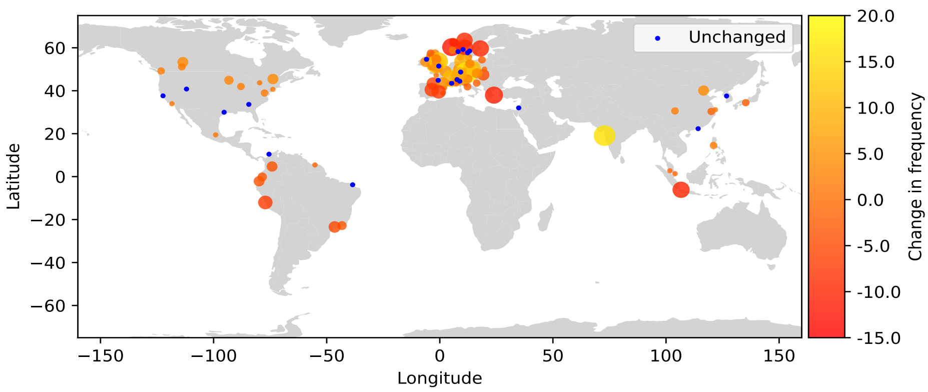
Table A1. *Cont.*

ISO Airport	ODs	Times Visited (LISO) (Week)	ISO	LISO
GUU	AMS–YYC, YYC–AMS	18	×	×
HRK	DEL–AMS, AMS–DEL	12	×	×
PFJ	YEG–AMS, AMS–YEG	9	×	×
SPC	CTG–AMS, AMS–PBM, BOG–AMS, PBM–AMS, GYE–AMS, LIM–AMS	1	×	×
TOF	ICN–AMS, KIX–AMS, AMS–KIX, AMS–PEK, PEK–AMS, AMS–ICN	17	×	×
URC	PVG–AMS, AMS–PVG	6	×	×
VXE	GRU–AMS, AMS–GRU	3	×	×
YBI	AMS–IAH, IAH–AMS, YYZ–AMS, AMS–YYZ	6	×	×
YDF	ATL–AMS, AMS–ATL	2	×	×
YGR	AMS–IAD, IAD–AMS	1	×	×
YHA	AMS–YUL, YUL–AMS	8	×	×
YJT	JFK–AMS, AMS–JFK	3	×	×
YMN	AMS–SFO, AMS–LAX, ORD–AMS, AMS–MSP, SLC–AMS, AMS–ORD, MSP–AMS, SFO–AMS, LAX–AMS	6	×	×

Table A2. Candidate intermediate stop-over airports for TAP network.

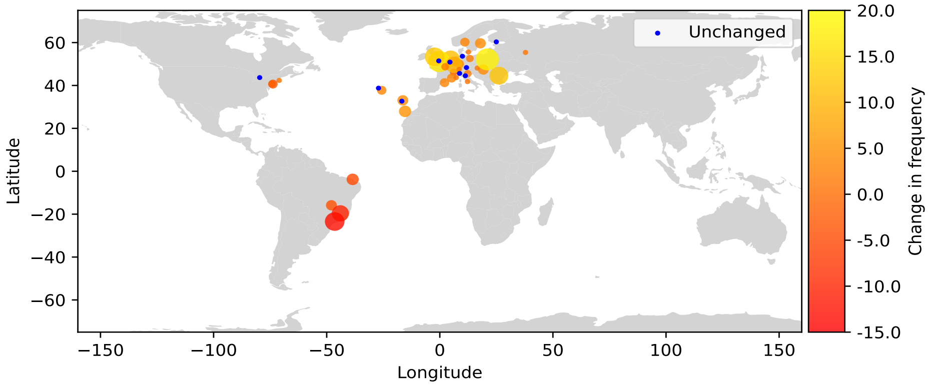
ISO Airport	ODs	Times Visited (LISO) (Week)	ISO	LISO
CVU	BOS–LIS, LIS–EWR, LIS–BOS, LIS–JFK, EWR–LIS, JFK–LIS	47	×	×
FEN	CNF–LIS, LIS–CNF	8	×	×
MQC	LIS–YYZ, YYZ–LIS	3	×	×
MVF	GRU–LIS, LIS–GRU	16	×	×
SID	LIS–REC, REC–LIS	2		×
SNE	NAT–LIS, LIS–NAT	2		×
VDE	FOR–LIS, LIS–FOR	1	×	×
VXE	BEL–LIS, BSB–LIS, LIS–BSB	2	×	×

Appendix B. Weekly Frequency Changes of Network (S-High)



(**a**)

Figure A1. *Cont.*



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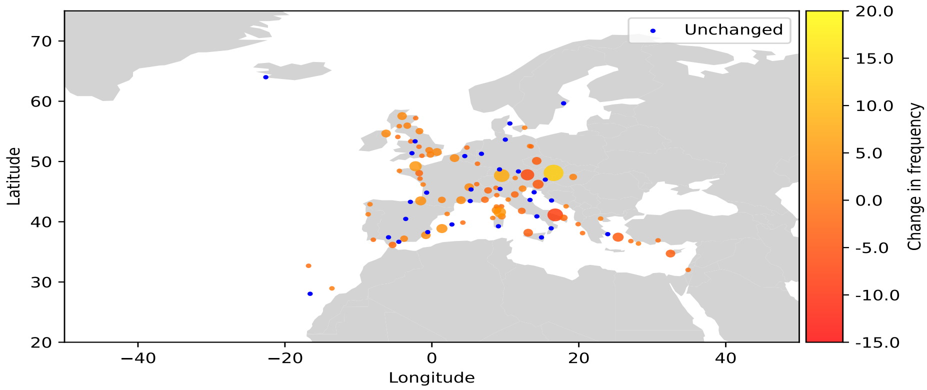

(**c**)

Figure A1. Weekly frequency changes of representative airlines—S-high: (**a**) weekly frequency changes of the routes in the network—KLM; (**b**) weekly frequency changes of the routes in the network—TAP; and (**c**) weekly frequency changes of the routes in the network—EasyJet.

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