

## Opportunistic commercial formation flights in continental airspace for greener aviation

Oriol Bracons Escarré<sup>a</sup>,<sup>\*</sup>, Christian Eduardo Verdonk Gallego<sup>b</sup>, Miquel Angel Piera Eroles<sup>a</sup>

<sup>a</sup> Dept. of Telecommunications and Systems Engineering, Autonomous University of Barcelona (UAB), Emprius Street 2, Sabadell, 08202, Barcelona, Spain

<sup>b</sup> ATM Research and Development Reference Centre (CRIDA), Parque Empresarial Las Mercedes, San Blas-Canillejas, 28022, Madrid, Spain

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### ABSTRACT

At a time of growing demand in commercial aviation, it is important to establish a trade-off between environmental impact, efficiency, and capacity. This is assessed through the study of Air Streams under a multi-criteria approach that pave the way for the deployment of commercial Formation Flights in continental airspace. This study describes a methodology to design Air Streams that could foster an efficient opportunistic Formation Flights pairing among aircraft. An evaluation of the main traffic flows that make up European airspace is conducted, followed by the design of two Air Streams. An study of potential use and savings is carried out, to evaluate Air Streams and Formation Flights synergy. The results of the heuristics applied show that Air Stream could manage around 10% of the aircraft flying in the airstream nearby area implementing Formation Flights. Significant savings could be achieved by the combination of Air Streams and Formation Flights concepts. The study estimates over 1600 tonnes of Fuel and over 5000 tonnes of CO<sub>2</sub> savings annually, only with the use case scenario evaluated.

### 1. Introduction

The Air Traffic Management (ATM) system has been designed to safely and efficiently organize and manage air traffic, operating an airspace divided into sectors with a limited capacity to handle thousands of flights every day by Air Traffic Controllers (ATCos) (Prandini et al., 2011). The increase in traffic demand can saturate the capacity of Air Traffic Control (ATC) systems, and therefore increase the need to fly longer distances and operate at non-optimal Flight Level (FL) to meet capacity constraints, while also raising the complexity of ATCo tasks (Isufaj et al., 2021; Delahaye et al., 2022). Furthermore, the impact of aviation pollutant emissions on the climate introduces new sustainability requirements at the management level, aiming to achieve more efficient traffic flows that reduce fuel consumption in daily aircraft operations.

Several strategies can directly reduce fuel consumption, ranging from new materials (Timmis et al., 2014) and/or technologies (Yusaf et al., 2024) to the strategic management of traffic flows (Grabbe et al., 2012). This study extends current ATM strategies by mitigating some inherent inefficiencies that negatively impact the environment. Currently, with the expansion of Free Route Airspace, routes with fewer restrictions and more direct paths are allowed, which significantly reduces flight time and consequently decreases fuel consumption and

pollutant emissions (Gencoglu and Baspinar, 2023). However, conflict resolution adjustments may require inefficient maneuvers due to closure angles and the increase in the number of potential conflict points.

The use of ATM strategies that ensure lower fuel consumption directly impacts the amount of fuel planned for the flight, which reduces the total weight of the aircraft and thus positively affects flight performance by further decreasing fuel consumption (Hassan et al., 2021; Walter et al., 2023).

It is worth noting that the mentioned traffic complexity and environmental impact issues are not exclusive to the aviation sector. Similar challenges can be found in other traffic systems, where different entities competing for access to the same space at the same time create spatio-temporal interdependencies (Borràs et al., 2024), negatively affecting overall system performance, as reported in urban traffic (Wen et al., 2017), maritime traffic (Wen et al., 2015), or logistics networks (Cheng et al., 2014). All these systems share the need for new cooperative management rules that support demand increases while avoiding the negative consequences of complex traffic and reducing environmental impact. Some proposed solutions rely on aggregating transport demand into efficient flows to prevent overloading resources used simultaneously. However, when flows increase to distribute traffic, the

\* Corresponding author.

E-mail address: [oriol.bracons@uab.cat](mailto:oriol.bracons@uab.cat) (O.B. Escarré).

Braess paradox (Ma et al., 2019) may occur, where “counterintuitively” adding new flows can increase congestion.

Given the particular challenges of the air traffic system, the Single European Sky ATM Research (SESAR) program has been established in Europe to modernize and enhance ATM within European airspace, aiming to achieve a Single European Sky, thereby unifying all airspace and improving efficiency, safety, and sustainability (Bolić and Ravenhill, 2021). A similar program exists in the USA: the Next Generation Air Transportation System (NextGen) program (Dunlay and Rakas, 2011).

Furthermore, cooperative mechanisms designed for ATM, such as Collaborative Decision Making (CDM) (Ball et al., 2001), have also been implemented in maritime traffic management (Lind et al., 2018) and User-Driven Prioritization Processes (UDPP) (Pilon et al., 2021), with applications to warehouse logistics networks where agent interaction is key to optimal traffic management, potentially improving Key Performance Indicators.

Cross-sector methodologies require a thorough analysis of enablers and barriers for successful deployment. The methodological approach described in this paper relies on enablers from car-following technologies, which improve vehicle coordination on high-density roads and are leveraged by aircraft manufacturers through a new aircraft-follow-aircraft technology, already tested in the Fello’Fly Project (Airbus, 2024).

In the context of growing air traffic demand EUROCONTROL (2018), it is important to consider the emissions generated by aviation, which some studies estimate to account for 2.4% of global annual CO<sub>2</sub> emissions (Klower et al., 2021; Planes et al., 2021). This paper presents a new cooperative approach to enhance potential fuel savings through opportunistic commercial Formation Flights (FF), evaluating their barriers in continental airspace.

### 1.1. Atlantic formation flights

Formation Flight (FF) is described in Liu and Stumpf (2018) as two correctly positioned aircraft utilizing the vortex generated by the wings of the leader aircraft to achieve a reduction in fuel consumption by the trailing aircraft. The Fello’Fly project carried out by Airbus, in which two A350s performed an oceanic test formation flight on November 9, 2021, from Toulouse, France, to Montreal, Canada, demonstrated reductions in traffic complexity and fuel consumption.

Building on these pioneering results, an industrial research project led by Airbus, Gain Environmental Efficiency by Saving Energy (GEESE) (European Commission, 2023b), aims to analyze the industrialization of FF procedures in the Atlantic and evaluate their feasibility in continental airspace from a holistic perspective. In addition, an increase in airspace capacity is expected, as the pair becomes a single entity for ATC. In continental airspace, air traffic complexity is one of the main barriers for FF, as conflict-avoidance maneuvers can not only increase fuel consumption but also pose safety risks, given that the distance between the two planes forming the flight pair is 1–2 nm, and separation is delegated to the pilots. FF could not only reduce fuel consumption, but also decrease traffic complexity, since both aircraft act as a single agent for ATC, reduces the number of flights to control.

FF operations are structured into five main phases: rendez-vous, catching-up, join-up, formation keeping, and split. The computation of the correct rendez-vous and split waypoints is a complex multi-criteria optimization problem in continental airspace, which also depends on the needs of each aircraft, the geometry of each trajectory, and the performance of the aircraft involved.

- **Rendez-vous:** Aircraft proceed to their meeting point, which is a common trajectory point, within a time window suitable for executing the operation.
- **Catching-up:** Maneuver in which the aircraft pair closes the longitudinal gap while remaining vertically separated, prior to the transfer of separation responsibility to the aircraft pair.

- **Join-up:** Maneuver in which the aircraft pair closes the lateral and vertical gap once leader-follower separation responsibility has been transferred to the aircraft pair, and the follower moves into its final position.
- **Formation Keeping:** Phase in which both aircraft are correctly positioned and can start benefiting from fuel savings.
- **Split:** Marks the end of the formation segment, at which point both aircraft separate and proceed to their respective destinations.

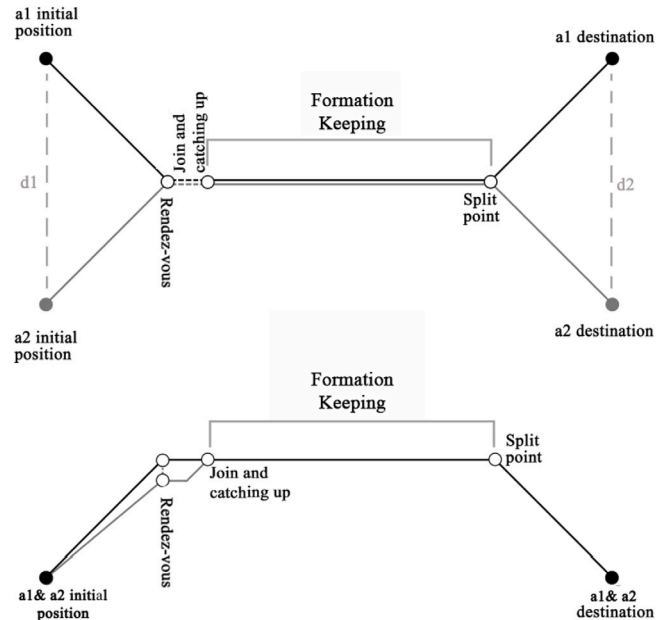


Fig. 1. Formation flight phases, horizontal and vertical profile.

Fig. 1 shows the different phases and segments of a FF both vertically and horizontally, where a1 and a2 are the aircraft involved. The initial waypoint is where aircraft adjust their original trajectories until they meet at the merge point to initiate the rendez-vous maneuver and start formation keeping, maintaining the necessary distance and speed until the split point, where the aircraft resume their courses to their respective destinations. At the merge point, it is necessary to set a Request Time of Arrival, as the aircraft must arrive at the correct time to ensure the distance required for formation is maintained before initiating rendez-vous. During the formation-keeping phase, the follower aircraft receives information from the leader aircraft for its control laws (lateral, vertical, and longitudinal) to automatically achieve and maintain the ad-hoc positioning relative to the leader’s vortex, through an automated system in which the leader shares all aircraft parameters.

In continental airspace, dense traffic areas are an important enabler for identifying potential FF candidates but also present several barriers. FFs require conflict-free routes, as conflict-avoidance maneuvers can compromise formation keeping. In continental airspace, the complexity and number of aircraft are higher than in the Atlantic, increasing the probability of en-route conflicts. FFs can be planned in advance before takeoff, defining the aircraft, route, rendezvous, and split points. However, in continental traffic, this approach has low tolerance for unforeseen events, a delay in one aircraft may mean that the necessary times or positions for FF are not met. In such environments, where regulations, route changes, and delays are common, pre-planned FF may not be suitable. Alternatively, the optimal pairing can be determined once the aircraft are en-route, known as Opportunistic FFs. This requires a real-time Pairing Assistance Tool that evaluates pairing candidates based on their flight plan and probability of en-route conflicts, avoiding the impact of ground delays on planned FF.

The Pairing Assistance Tool evaluates a new trajectory for performing the FF, which may increase or, in some cases, decrease flight

distance relative to the original plan. Additionally, to meet the Request Time of Arrival, the aircraft may need to adjust its speed. These modifications can result in an increase or, exceptionally, a decrease in fuel consumption. To evaluate these factors, the Benefit Deviation Rate (BDR) is established for distance, taking into account the potential increase in fuel consumption and serving as a key indicator when searching for opportunistic flight pairs.

### 1.2. Air Streams

The Air Stream (AS) concept refers to a designated route created for aircraft with the aim of optimizing flight trajectories, increasing airspace capacity, and reducing potential conflicts between aircraft. These routes are strategically planned and coordinated, considering factors such as airspace capacity, traffic demand, meteorological conditions, and other operational parameters.

AS are designed to manage traffic following common flow patterns across the airspace, to ensure that aircraft operating within the AS generates minimal workload for ATCo. An AS is formed by multiple lanes and levels with designated entry and exit points. A key characteristic that distinguishes AS from current traffic flows is the presence of specific entry and exit points, which allows for the management of aircraft separation and speeds upon entry. With this concept, aircraft can navigate efficiently inside the AS encountering minimal interference from surrounding traffic, and allowing conflict-free routes (SESAR Joint Undertaking, 2024).

This concept is currently being evaluated by the SESAR Flight Centric ATC project (FCA) (European Commission, 2023a), with the objective of reducing ATCo workload and enhancing productivity.

### 1.3. Sector optimization

Within European airspace, several sectors present complex traffic patterns. For illustrative purposes, consider the LECMSAI sector, located in northern Spain, which exhibits considerable complexity as it absorbs traffic from south to north and from east to west. This traffic is not only European but also includes flights originating from both South and North America. Additionally, this sector may serve as a suitable location for conducting rendez-vous or split operations for aircraft performing an oceanic FF.

As observed in Fig. 2, this sector has traffic coming from multiple directions. When performing an FF that crosses a sector with this level of complexity, potential conflicts along the route must be carefully considered.

Fig. 3 corresponds to a 24-hour simulation using the initial traffic (scheduled flight plans), in which potential conflicts between trajectories in the LECMSAI sector are analyzed. A total of 321 conflict points are observed. The development of a new methodology to support conflict-free commercial FF could have a significant positive impact in sectors such as LECMSAI, reducing traffic complexity and ATC workload, while simultaneously decreasing fuel consumption for FF aircraft and contributing to a reduction in aviation's environmental impact.

FF represents a new ATM strategy for reducing fuel consumption, while AS provides a new structure for clustering main flows within the airspace. AS provide main routes with higher traffic density, which FF could benefit in order to enhance pairing probability. Furthermore, AS reduce ATCo workload while increasing capacity, since traffic is divided into main flows and the separation is guaranteed within the AS. This presents conflict free routes, which FF can also benefit. Despite the relevant synergy among AS and FF, the combination of both, to the best of authors knowledge, have not been analyzed in the literature, neither the synergies integrating FF in As have been reported.

To address this gap, the paper is organized as follows: first, a review of the literature and the current context of FF is presented. Subsequently, the methodology for AS and traffic flows within European airspace is described, focusing on two main flows by implementing an AS for each flow, and then analyzing its potential use by regular traffic and FF. Finally, the results are evaluated in the conclusions. Main acronyms used in this paper are defined in Table 1.

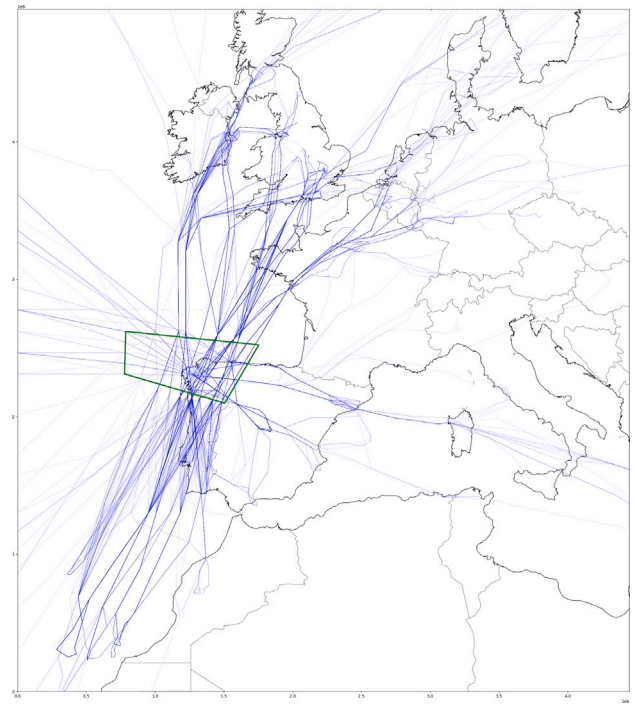


Fig. 2. LECMSAI sector with all daily traffic.

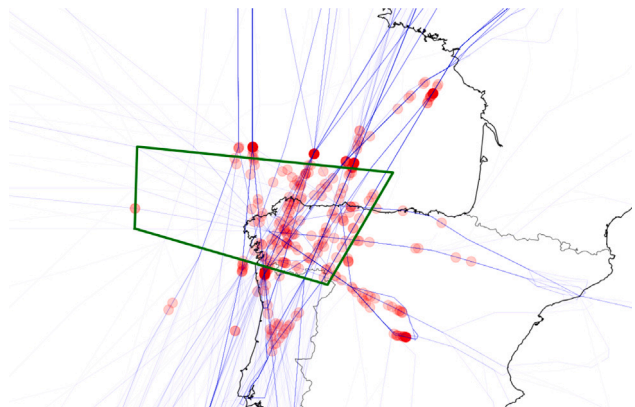


Fig. 3. LECMSAI potential conflicts detected.

## 2. Related work

Inspired by migratory birds, which use V-shaped formations to save energy (Hummel, 1983), FF utilize similar physics to reduce fuel consumption, thereby decreasing pollutant emissions and flight costs (Kent and Richards, 2021).

Several studies conclude that FF can lead to fuel savings (Dahlmann et al., 2020a; Escarré et al., 2024), which directly impact daily operations. Within the GESE project (European Commission, 2023b), Airbus conducted the Fello'Fly (Anon, 2024) flight test to estimate fuel savings (Airbus, 2024), in which two A350s performed an FF on November 9, 2021, from Toulouse, France, to Montreal, Canada. The route, waypoints, as well as rendez-vous and split points, were established prior to the flight, achieving significant fuel savings.

To date, FF within continental airspace have not been evaluated. Various studies assess their climatic impact (Dahlmann et al., 2020b), accounting for the reduction in fuel consumption and, consequently, pollutant emissions. One of the key challenges of FF is managing maneuvers during the formation flight. Given the close separation

**Table 1**  
Acronyms.

Acronyms	
ATM	Air Traffic Management
ATCo	Air Traffic Controller
ATC	Air Traffic Control
FL	Flight Level
FF	Formation Flight
ToC	Top of Climb
ToD	Top of Descent
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
BDR	Benefit Deviation Rate
RCF	Reduced Contingency Fuel
AS	Air Stream
SDB	Spatial Data Base
AIRAC	Aeronautical Information Regulation and Control
GEESE	Gain Environmental Efficiency by Saving Energy
Kg	Kilograms
s	Seconds
FCA	Flight Centric ATC Project

distance, any maneuver can compromise flight safety with surrounding traffic. Therefore, a main objective for FF is the optimal calculation of routes, considering not only the trade-off between maximizing fuel savings during formation keeping and deviations from the optimal rendez-vous trajectory, but also minimizing complexity caused by the spatio-temporal interdependencies between FF maneuvers and surrounding traffic.

Several studies address airspace complexity through route analysis using conflict detection and resolution algorithms (Zúñiga et al., 2013) to evaluate trajectories and reduce conflict impact. However, route studies specifically for FF, incorporating conflict detection algorithms, have not yet been evaluated. Some papers address the calculation of optimal routes and points of intersection and separation for FF, which are key to ensuring maximum fuel savings during flight (Xu et al., 2014; Hartjes et al., 2019).

The concept of AS is introduced in Guichard et al. (2005), Athènes et al. (2002), establishing corridors within the airspace to distribute traffic along different FLs and horizontal separations, creating a main tube. This allows traffic within the AS to maintain a constant speed and altitude while providing priority over surrounding traffic, resulting in conflict-free corridors.

Within the AS, the calculation of corridor positioning is crucial. Strategic positioning can significantly increase AS utilization. It is essential to evaluate the busiest routes and potential intermediate entry and exit points to enhance AS usage, while ensuring that all requirements for FF operations are met. Some studies use clustering to identify traffic flows, analyze trajectories, and make predictions (Conde Rocha Murca et al., 2016; Olive and Morio, 2019). For AS, other studies evaluate clustering as a method to identify corridor positioning (Dohy et al., 2021).

Various algorithms and approaches exist for traffic clustering. Two methods stand out: K-means/K-medoids and Density-Based Spatial Clustering of Applications with Noise (DBSCAN). Andrienko et al. (2018) analyze trajectories of vehicles, people, hurricanes, etc., using K-means/K-medoids, demonstrating its adaptability to different environments. DBSCAN can also be used for trajectory clustering among other applications (Bolić et al., 2022). Given the variety of methods, some studies compare the performance of different algorithms (Gallego et al., 2018).

Although AS and FF have been studied separately in two different SESAR projects GEESE for FF (European Commission, 2023b) and FCA for AS (European Commission, 2023a), the terms of design and potential implementation, their joint use in continental airspace, including methodology or evaluation with real traffic, has not yet been explored. This study presents an implementation methodology with a use case, aiming to provide new approaches to address this research gap.

### 3. Methodology

The main goal of this paper is to evaluate a rigorous approach for the efficient implementation of FF within continental airspace, taking into account the various barriers they present, as discussed in Section 1.1.

#### 3.1. Data and traffic flows

Aeronautical Information Regulation And Control (AIRAC) (ICAO, 2021) is a system used for the regulation and distribution of aeronautical data. The AIRAC system operates on 28-day cycles, during which amendments and updates to navigation charts, approach procedures, airspace restrictions, and other information relevant to the safety of air navigation are published.

The data used in this study comes from AIRAC\_2303\_502, which contains information from March 23, 2023, to April 19, 2023. Data used in this paper for the analysis corresponds to March 31, 2023, which includes a total of 28,270 flights overflying European airspace.

Considering the benefits of FF in Atlantic airspace, traffic organization in the Atlantic has been analyzed through the use of Tracks, to explore how AS could implement similar traffic conditions in continental airspace. These Tracks are adjusted daily according to weather conditions to optimize wind usage and reduce fuel consumption. Depending on the time of day, flows are mostly concentrated in an easterly or westerly direction, and these flows are typically uni-directional. Additionally, Tracks can be structured by FL and are governed by longitudinal and vertical separation between aircraft on the same track. AS can be implemented in a similar manner for use in continental airspace.

Since the implementation of FF in continental airspace requires conflict-free routes, the following methodology is applied to evaluate the implementation of AS, which provides conflict-free routes within European airspace.

European airspace accommodates a large number of daily flights, yet main traffic flows can be observed through which most aircraft are routed. To evaluate the implementation of an AS, it is essential to identify the primary flows that structure European airspace. Therefore, it is necessary to analyze the origins and destinations contained in the dataset.

By examining the first letter of the International Civil Aviation Organization (ICAO) codes for the origin and destination of flights in the dataset, it is possible to identify flows between European regions. Flows are counted without considering the direction of the flight, only the region pair.

Fig. 4 shows the top 10 flows within Europe. As observed, the main routes connect Northern Europe and Southern Europe. Other

Distribution of Traffic Flows

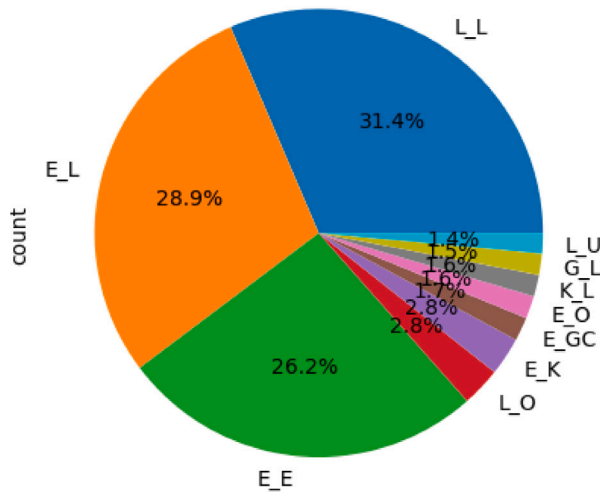


Fig. 4. Distribution of traffic flows within continental airspace.

Table 2  
Region letter definition.

Letter	Region
E	North Europe
L	South Europe
O	Asia
K	United States
GC	Canary Islands

significant flows include South Europe to Western Asia (O), Northern Europe to the United States, and Northern Europe to the Canary Islands. Corresponding letter of each region is defined in Table 2

For the implementation of an AS, it is important to consider the traffic volume it can accommodate. Therefore, it is necessary to identify the most congested flows. Similarly, for FF, it is important to evaluate flows and flights with longer distances, as these would increase the shared flight segment and, consequently, fuel savings.

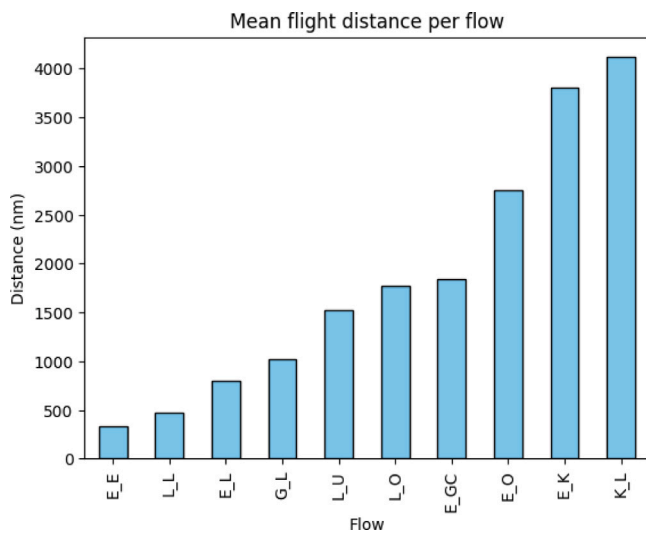


Fig. 5. Average flight distance by flow in nautical miles (nm).

As Fig. 5 shows, the mean flight distance for each flow, with flights within Europe exhibiting the shortest mean distances, while intercontinental flights have the longest mean distances.

3.2. Air Stream design

For the implementation of AS in this flow, the DBSCAN algorithm will be used for traffic data clustering. Unlike K-means, which searches for clusters based on distance to centroids, DBSCAN identifies clusters based on density. Therefore, to maximize the utilization of the AS by aircraft, DBSCAN is more suitable for the objectives of this study. Using the K-Nearest Neighbor(NN) distance, the point with the highest density will be selected as the entry/exit point for the AS.

A flight consists of three phases: climb, which starts at takeoff and ends once the desired altitude is reached, cruise, where most of the flight takes place, and descent, where the aircraft descends until reaching its destination. The points at which phase changes occur are called Top of Climb (ToC) and Top of Descent (ToD). To calculate the start and end points of the AS, the ToC and ToD of the selected flights will be used. This ensures that the beginning and end of each AS align with the cruise phase of the aircraft that will use them.

Within the AS, both FF and conventional flights will share the airspace to maximize its utilization. Therefore, intermediate entry and exit points will be implemented for the AS, allowing traffic outside the analyzed flow to benefit as well. To achieve this, trajectories not belonging to the selected flow but with origins or destinations in countries near the AS resulting from the combination of points generated from the ToC and ToD analysis will be evaluated. Only points corresponding to the climb and descent phases will be selected. This results in different clusters, mostly corresponding to the densest traffic zones of European airspace near the AS, which can be used to implement intermediate points that absorb traffic from these areas.

The DBSCAN method requires setting two parameters to define cluster boundaries: epsilon, which represents the maximum distance to consider two points as neighbors, and minPts, the minimum number of neighbors a point must have within that radius to form a cluster. By establishing appropriate values for epsilon and minPts, clusters with the highest density can be identified to create the AS. Next, K-NN can be applied to determine the densest point within each cluster. This point will be selected as the location to implement in the AS, as it corresponds to the area with the largest number of aircraft.

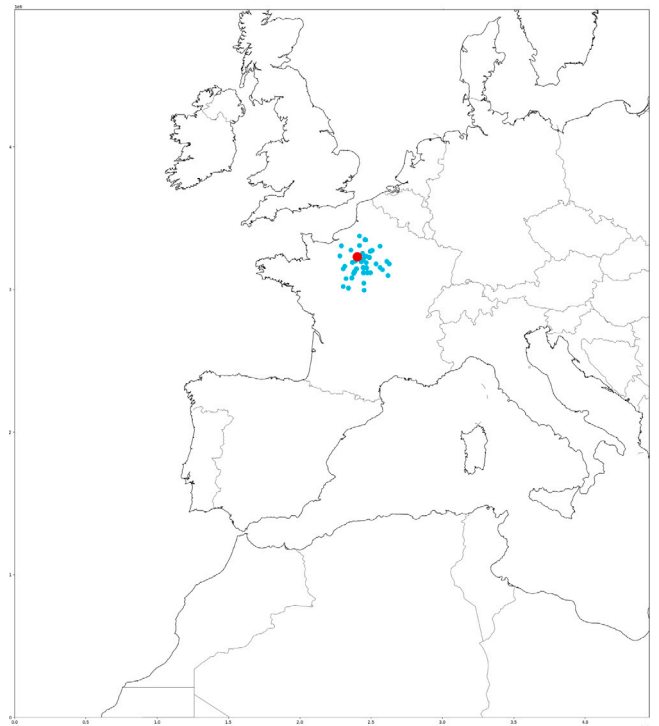


Fig. 6. Example of a cluster and resulting density point.

Fig. 6 shows a cluster (blue points) calculated using DBSCAN. The red point represents the densest point in the cluster, obtained by applying K-NN. This process will be applied to the selected data, enabling the creation of the Air Stream and adapting it to the needs of the selected flow.

### 3.3. Air Stream utilization and formation flight

To estimate the potential use of the AS, all trajectories can be analyzed individually to identify flights with the highest likelihood of utilizing the AS. This analysis may require significant computational effort. To optimize the search, the following approach is implemented: the AS is evaluated in segments, each defined by the distance between consecutive points forming the AS. This creates a rectangular search area for each segment, accounting only for aircraft whose trajectory includes at least one point within any of the AS search areas. This approach also allows the assessment of AS usage per zone. Finally, by comparing the azimuth of the AS and the trajectory, flights with a direction similar to the AS are identified.

- $|\text{azimuth Air Stream} - \text{azimuth flight}| \leq 5$  #Similar slope
- **One or more trajectory point inside AS zone** #Route near Air Stream

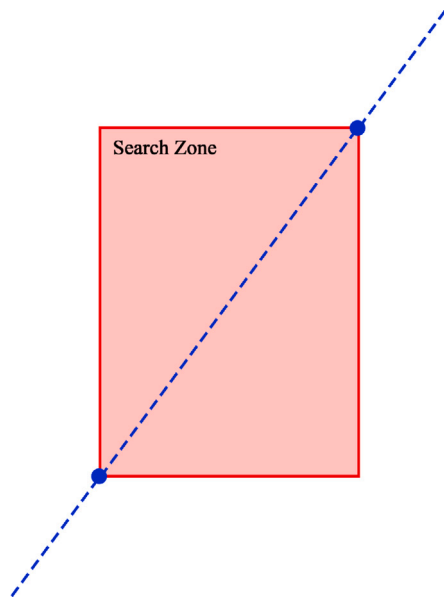


Fig. 7. Example of an Air Stream search zone.

Fig. 7 shows the search zone (in red) used to identify flights passing near the AS (in blue).

In this paper, the estimation of FF potential is performed using a Spatial Data Base (SDB) to search for spatiotemporal coexistence, combined with a heuristic, as described in Escarré et al. (2023), and shown in Fig. 8. By dividing the airspace, it is possible to efficiently identify aircraft that are close in space and time. The heuristic provides criteria to discard aircraft unlikely to form FF pairs and to prioritize those with the greatest potential for performing FF. Once aircraft with FF potential are identified, they are compared with the aircraft identified in Section 3.3, allowing for the determination of aircraft with potential both to use the AS and to perform FF, which are then included in the final calculations.

### 3.4. Benefit evaluation

The implementation of the AS may require modifications to the original flight plan, which in some cases can increase or decrease the

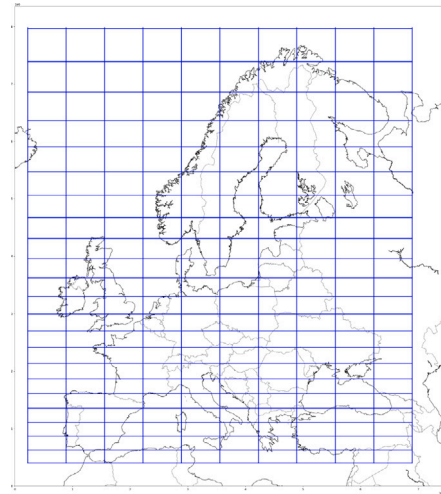


Fig. 8. Spatial Data Base over Europe.

planned flight distance. The Benefit Deviation Rate (BDR) is used to evaluate the maximum allowable distance deviation while still achieving fuel savings. To calculate this, the fuel savings provided by an FF must be considered.

Fuel consumption was estimated using BlueSky (Hoekstra and Ellerbreek, 2016) and its performance model OpenAP (Sun et al., 2020), which were used to perform the simulations and calculate fuel usage.

To determine the maximum allowable deviation distance, both the fuel savings from FF and the potential savings from using the AS must be considered. Previous research suggest that FF can result in approximately 3.03% fuel savings (Escarré et al., 2024), this will be the assumed fuel savings for this study.

$$\text{BDR}_d = \frac{(f_{ct} \cdot d) - (f_{as} \cdot k \cdot d)}{f_{ct}} \quad (1)$$

Where:

- $f_{ct}$  = Average fuel consumption in Kg/nm for common traffic.
- $f_{as}$  = Average fuel consumption in Kg/nm for Air Stream traffic.
- $d$  = FF shared distance (formation keeping phase).
- $k$  = Fuel Save coefficient, to assess the FF fuel save (3.03%)

To illustrate the use of the proposed BDR describes in Eq. (1), two simulation scenarios are established to obtain the values of  $f_{ct}$  and  $f_{as}$ .

- **SCN0:** This is the baseline scenario. It is created using real flown traffic data obtained from the AIRAC dataset, including only flights in the cruise phase that belong to the selected traffic flow and use the selected aircraft model. SCN0 contains the actual trajectories, with all vertical and horizontal deviations, as well as the corresponding speeds. This scenario serves as the reference to establish the standard average fuel consumption for flights in the selected flow. The resulting fuel consumption from this scenario is represented by the variable  $f_{ct}$ .
- **SCN1:** This scenario simulates flight conditions using the AS. It is assumed that only traffic within the AS follows conflict-free routes and can therefore maintain the standard Mach cruise speed for the selected aircraft and flight level throughout the entire AS trajectory. All other traffic operates under the same constraints as in SCN0. Fuel consumption is calculated for each AS obtained from the previous evaluations, and  $f_{as}$  represents the average consumption across all AS.

For aircraft selection, traffic is analyzed, and for simplicity, the most common aircraft type in the selected flow is chosen. The basic aircraft parameters such as cost index, initial weight, and aircraft type, are kept consistent for both scenarios, as established in OpenAP.

#### 4. Fuel weight impact

Considering that the use of FF and AS affects fuel consumption, and assuming that the implementation of FF ensures approximately 3.03% savings (Escarré et al., 2024), the initial dispatch fuel can be reduced by a similar amount. Consequently, either the Take-off Mass can be decreased or the Payload increased.

According to the European Union Aviation Safety Agency (EASA) Air Operations (AMC6 CAT.OP.MPA.181 (d)) (Easa, 2023), the Reduced Contingency Fuel (RCF) procedure can be considered. The RCF procedure specifies that if the operator’s fuel policy includes pre-flight planning to a destination 1 aerodrome (commercial destination with an RCF procedure using a decision point along the route) and a destination 2 aerodrome (optional refueling destination), the amount of required usable fuel calculated pre-flight can be reduced, provided certain conditions are met.

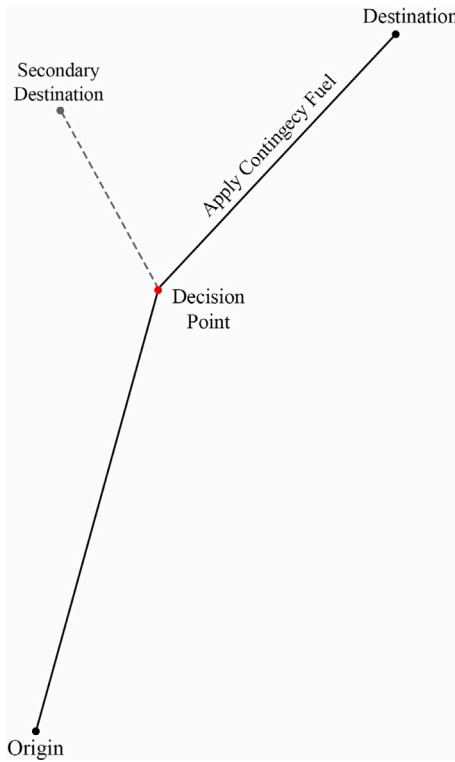


Fig. 9. Reduced Contingency Fuel Graph.

Contingency fuel is defined as an additional fuel load to account for uncertainties during flight and represents a percentage of the total trip fuel. Since contingency fuel can be substantial, it may significantly increase Take-off Mass and fuel consumption. By establishing a fuel plan with a secondary destination, contingency fuel is calculated only from the decision point. Upon reaching the decision point, pilots must check the remaining fuel and decide whether it is sufficient to reach the destination or if diversion to an alternate airport is required. The RCF procedure is illustrated in Fig. 9.

The RCF procedure could be applied to FF using a revised flight plan that incorporates the potential fuel savings. Considering the potential for aircraft pairing, a trade-off can be evaluated to determine whether the cost of possible diversions to an alternate destination compensates for the fuel savings achieved through FF operations.

To estimate the reduction in fuel consumption during FF, it can be calculated with the following equations:

$$AJ = \frac{1}{n} \sum_{i=1}^n j_i \quad (2)$$

$$R = IM - AJ \cdot ff\_t \quad (3)$$

$$FC_{std} = \sum_{i=0}^{n=ff\_t} (f1_i) \quad (4)$$

$$FC_{ff} = \sum_{i=0}^{n=no\_ff\_t} (j2_i) + \sum_{i=0}^{n=ff\_t} (j2_i \cdot (1 - k)) \quad (5)$$

$$FuelSave = FC_{std} - FC_{ff} \quad (6)$$

Where:

- *R* = Reduced Contingency Fuel Initial Mass (RCFIM) (kg)
- *IM* = Initial Mass (baseline) (kg)
- *AJ* = Average Fuel Flow (kg/s)
- *j* = Instant Fuel Flow (kg/s) *j*<sub>1</sub> = IM, *j*<sub>2</sub> = RCFIM
- *ff\_t* = Formation Flight time (s)
- *no\_ff\_t* = No Formation Flight time (s)
- *f\_t* = Standard Operation Flight time (s)
- *k* = FF Save coefficient (3.03%)
- *FC* = Fuel Consumed

An Initial Mass (IM) is established, and using Eq. (3), the estimated fuel savings can be calculated. These savings are subtracted from the Initial Mass to obtain the Reduced Contingency Fuel Initial Mass (RCFIM). OpenAP (Sun et al., 2020) is used to simulate the flight under identical parameters, with the only difference being the mass (IM and RCFIM). The IM simulation serves as the baseline, while the RCFIM scenario incorporates FF.

This reduction in mass results in lower fuel flow throughout the flight in the RCFIM scenario, and during the FF period, the additional reduction due to formation flying (coefficient) is also applied. Once both scenarios are simulated, with fuel flow recorded in kg/s and simulation steps corresponding to each second of flight, the total fuel consumption for each scenario is obtained by summing all steps, as described in Eqs. (5) and (4). The difference between the two scenarios, shown in Eq. (6), represents the total fuel saved in kilograms, using the IM scenario as a reference (flight without FF).

CO<sub>2</sub> emissions can be estimated by applying the ratio defined in EUROCONTROL; SESAR Joint Undertaking (2019), on the fuel flow results from Eqs. (5) and (4). This equations provide the total emissions and allow the calculation of CO<sub>2</sub> savings between the two simulations.

#### 5. Results

##### 5.1. Use case

By analyzing the results obtained in Section 3.1 (Flow Analysis), it can be observed that the flow between the Canary Islands (GC) and Northern Europe (E) is particularly significant, with the longest flight distances within continental airspace. Considering that the Canary Islands have only six international airports, the geographical position and limited size of the region make the volume of traffic notable: a total of 414 flights to or from Northern Europe, representing 1.46% of the total traffic overflying European airspace and 1.7% of the top 10 flows within Europe.

A closer examination of this flow (GC\_E) reveals that more than half of the traffic originates from just two countries: the United Kingdom, accounting for 46.37% of the flow, and Germany, accounting for 22.94%.

In Fig. 10, the different routes that form this flow are described, highlighting the main paths that make up this flow and how the traffic is primarily concentrated over Spain, Portugal and the LECMSAI sector.

The use case of this paper will focus on the evaluation of AS and FF for the flow of the Canary Islands, the United Kingdom, and Germany.

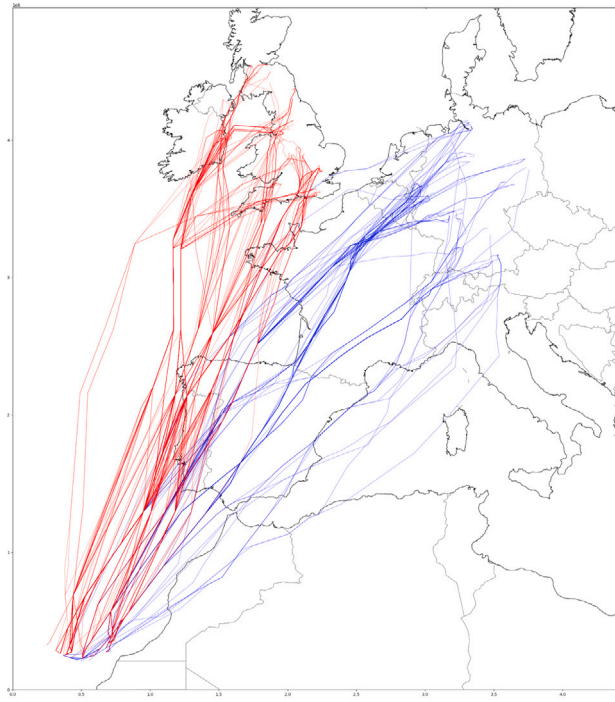


Fig. 10. Use Case selected flow.

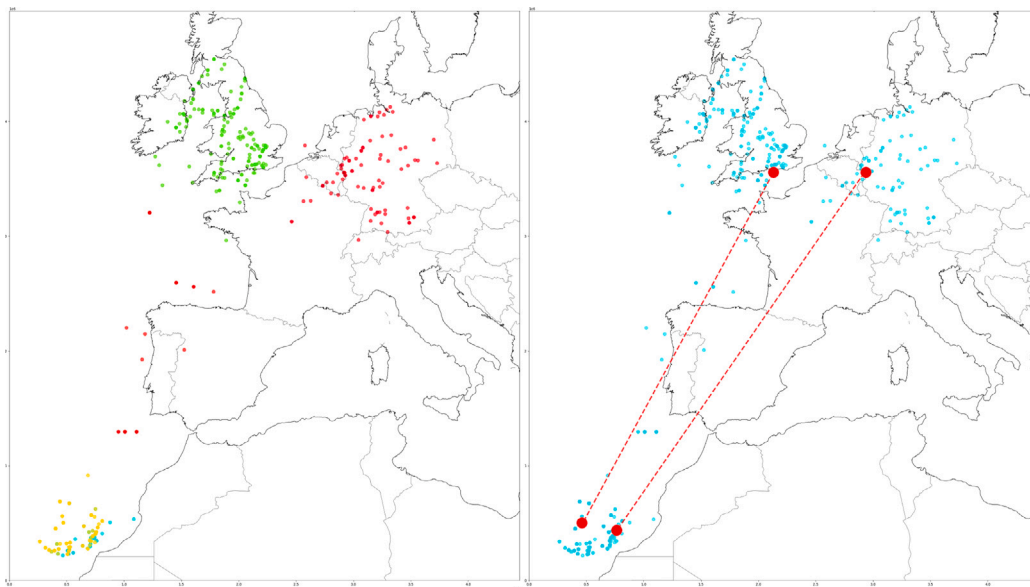


Fig. 11. ToC and ToD points over map, DBSCAN and resulting Centroid.

## 5.2. Air Stream

### 5.2.1. Initial and end points

By setting epsilon to 0.3 and minPts to 15 in the DBSCAN algorithm, we aim to identify meaningful traffic clusters from the simulated trajectory data. Through iterative testing and evaluation of different values, these were found to produce the most relevant clusters for AS formation in our case study. It should be noted that these values may vary with different datasets.

In Fig. 11, the clustering process is illustrated. In the left image, the four resulting clusters are shown in different colors. The clusters obtained from applying DBSCAN correspond to each flow, as they are calculated separately for greater precision. Once the clusters are

identified, the K-NN method is applied to determine the waypoints for each cluster's ToC and ToD with the highest density, as shown in the right image. These resulting centroids define the initial and end points of the AS.

### 5.2.2. Intermediate entry and exit points

Within the AS, both FF and conventional flights share the space to maximize utilization. Therefore, intermediate entry and exit points are implemented, allowing traffic not belonging to the Canary Islands, Germany, and United Kingdom flow to also benefit from the AS. To achieve this, trajectories not belonging to the initial flow but with origins or destinations in countries within the initial flow are analyzed. ToC and ToD points with a flight level below 250 are evaluated,

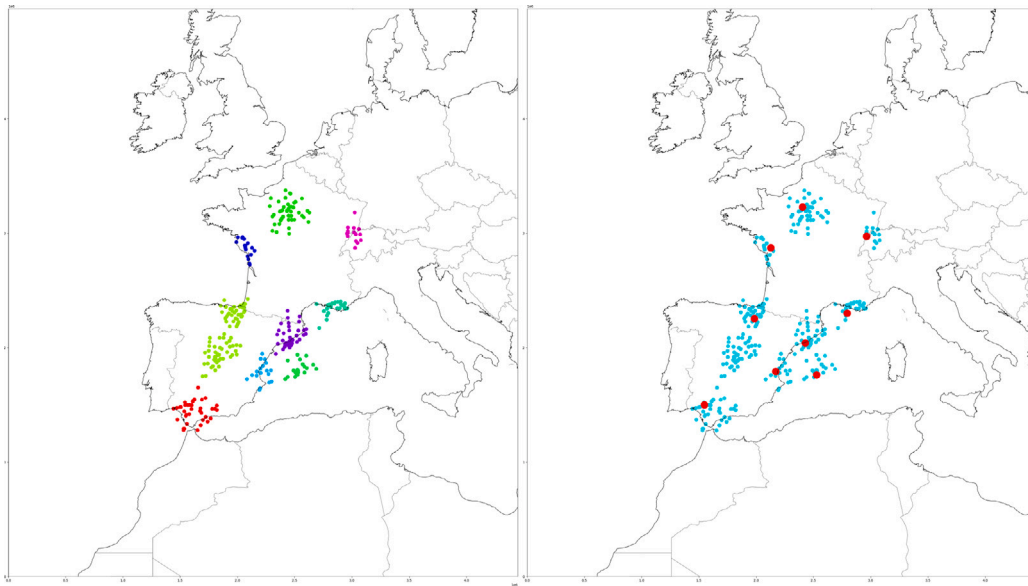


Fig. 12. Intermediate points over map, DBSCAN and resulting Centroid.

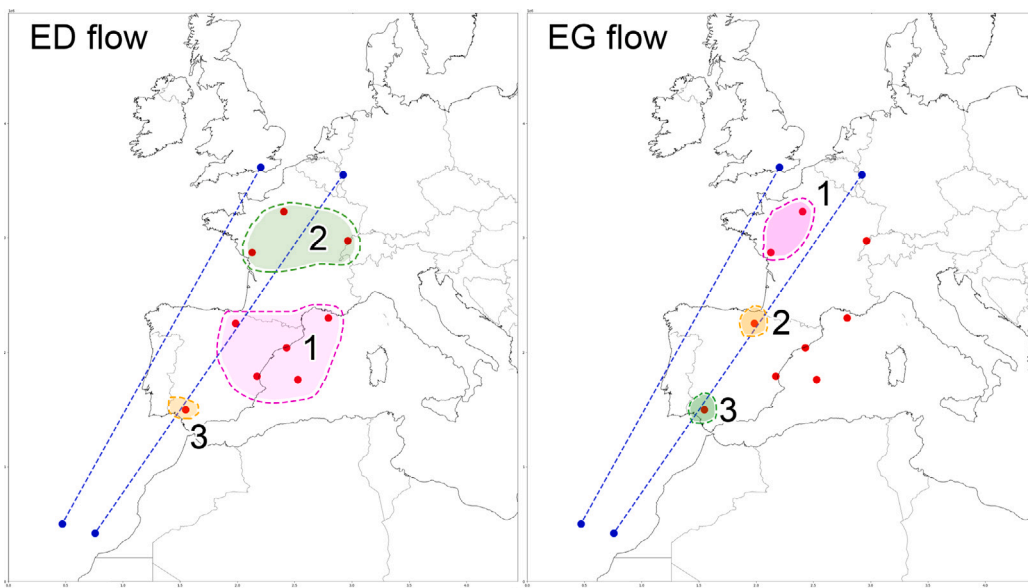


Fig. 13. Clusters to feed the Air Streams.

enabling the identification of trajectory segments corresponding to the ascent or descent phases of the flight.

For the DBSCAN algorithm applied to intermediate ascent and descent points, after iterative testing and evaluation, an epsilon of 0.1 and a min-pts of 60 were found to produce the best results to evaluate intermediate points, resulting in the following outcomes:

In Fig. 12, the left image shows the different intermediate clusters obtained from the DBSCAN algorithm, while the right image displays the resulting centroids (in red) calculated using the K-NN method. As can be observed, these centroids are primarily positioned in higher traffic density areas during the climb phase of European airspace.

To determine the entry and exit points for the AS, the intermediate points must be combined with the AS defined by the initial and final points.

Fig. 13 shows the different intermediate density points in relation to each AS. Depending on their distance from the AS and their positioning,

some points may be discarded. Based on these criteria, three intermediate entry and exit points are selected for the AS over Germany, corresponding to clusters that absorb traffic from France, Portugal, and Spain. For the United Kingdom, two intermediate points are generated, as it is farther from the identified density points.

### 5.2.3. Resulting Air Stream

Once the intermediate points, as well as the start and end points of the AS, are established, the following Air Streams are obtained:

Fig. 14 shows the resulting AS, including the names of each waypoint forming the stream. The German Air Stream has a total distance of 1548.64 nm, while the UK Air Stream has a total distance of 1440.42 nm. The names of the intermediate points correspond to the waypoints used for their calculation, although they do not represent the original positions. Therefore, the acronym of the AS to which they belong is appended to each name.

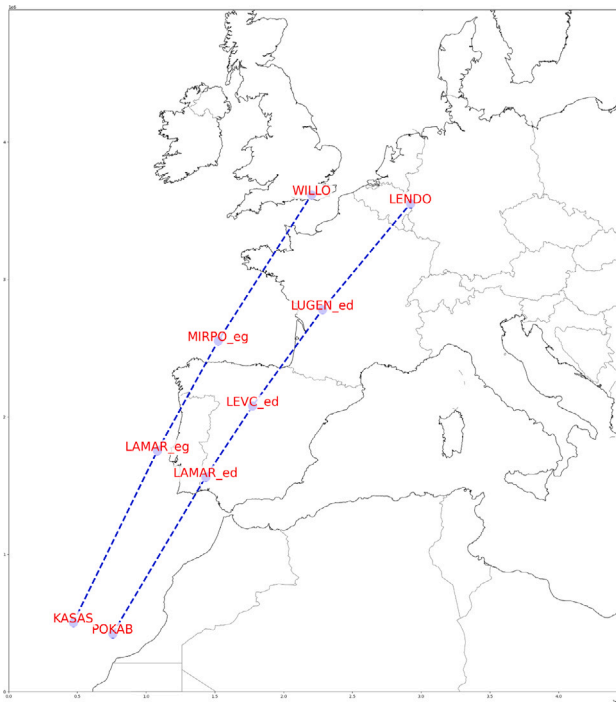


Fig. 14. Resulting Air Stream.

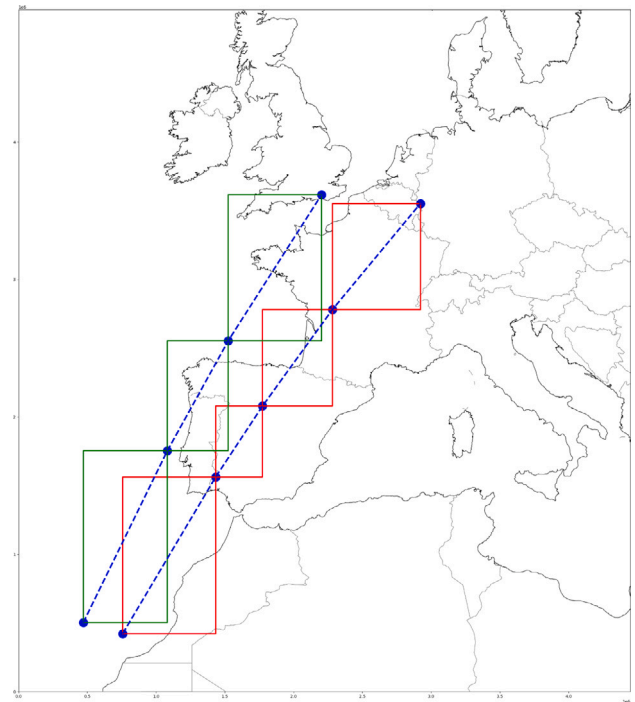


Fig. 15. Air Stream Search Zones.

For this study, the Single European Sky is assumed, where different countries cooperate and coordinate in ATM. Potential airspace restrictions were not evaluated for the positioning of the AS.

### 5.3. Occupancy estimation

Using the search zones and filtering criteria described in Section 3.3 of the Methodology, a filter is applied, resulting in the following outcomes:

Fig. 15 illustrates the different search zones of the AS. The dimensions of each zone depend on the segment distance. To evaluate occupancy, the coordinates of all trajectories are iterated over to determine whether any trajectory points fall within an AS zone. If a point lies within a zone, its azimuth is compared with that of the AS, allowing the identification and counting of trajectories with greater directional compatibility.

#### 5.3.1. Standard traffic

The result obtained gives a total of 560 aircraft that have the potential to use one of the AS.

As it can be observed in Fig. 16 the resulting compatible traffic found with the previous criteria, it is plotted in orange. As shown in this figure, not only continental traffic could benefit of the AS, but also traffic from South America could use this routes.

#### 5.3.2. Formation flights

Once the calculation of the SDB mentioned in of Methodology is applied a total of 52 aircraft among the 560 candidates have the potential to perform an opportunistic FF and use the AS designed, which represents 9.28% of the total number of aircraft that can use the AS.

By grouping the identified flights depending on their flow, the following values are obtained:

In Fig. 17, the probability to find a pairing candidate is observed according to the scenario being evaluated. Scenario 0 refers to the flow initially studied, from the UK and Germany to the Canary Islands,

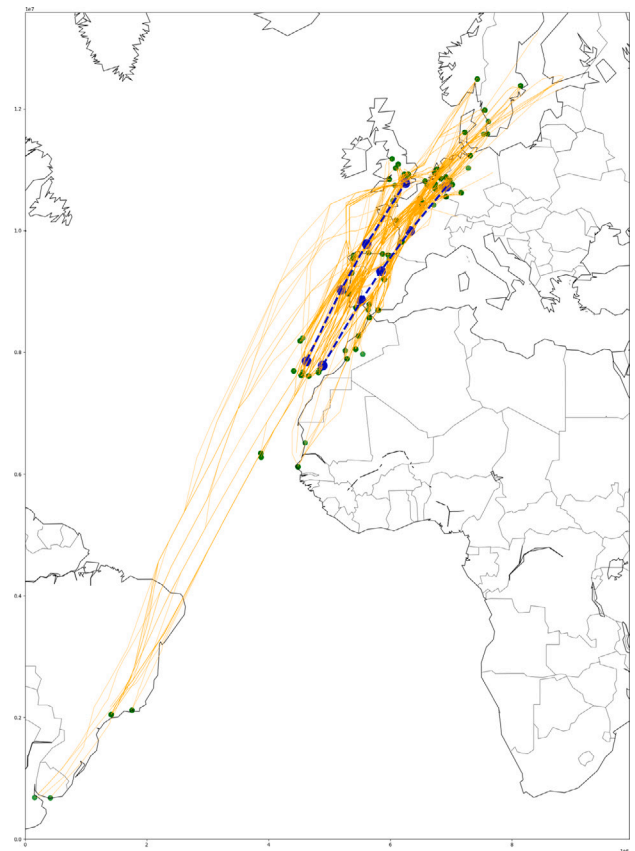


Fig. 16. Compatible found traffic over Air Stream.

where it has a 1.25% probability. Scenario 1 consists of Scenario 0 plus all those aircraft that can use the AS through intermediate entry and exit points, representing a total of 7.32%. Finally, Scenario 2 consists

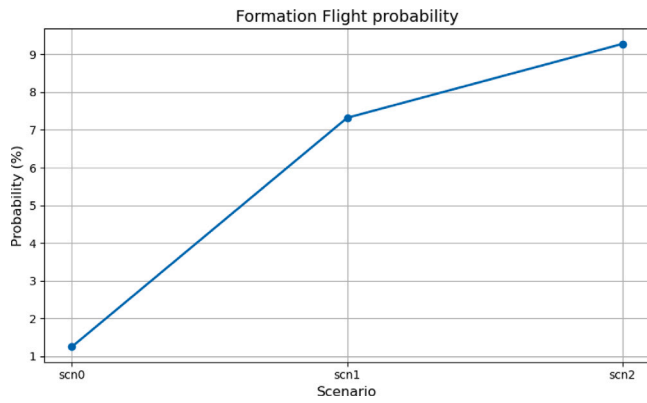


Fig. 17. Formation Flight probability.

Table 3  
Flight pair example data. (Dist in nm).

ID	ori	dest	time_dep	time_arr	total_dist	color
Flight1	GCLP	EDDK	174 300	214 535	1785.19	red
Flight2	GCTS	EDDF	175 100	214 350	1847.64	green

of all the previous ones and those flights with origin or destination in Africa, thus representing 9.28%.

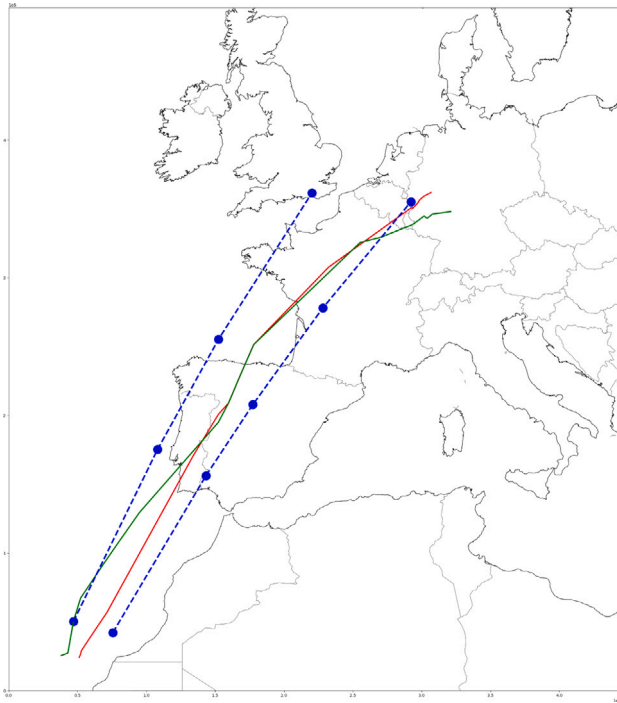


Fig. 18. Flight pair example plot.

5.3.3. Formation flight and AS result example

In Fig. 18 and Table 3, an example of one of the resulting FF and AS pair can be observed. In this case, the destination and origin airports are different, but it can be seen that the route is quite similar. These two aircraft have Germany as their origin, so the German AS could be use entirely, which represents a potential sharing over 80% of the planned flight distance.

5.4. Benefit deviation rate

The two scenarios mentioned in Section 3.4 of the Methodology are simulated using BlueSky and OpenAP. The simulations are based on the following assumptions:

- The B738 aircraft is used for both scenarios, since its the more common aircraft used on the use case flow.
- The Air Stream will allow airplanes inside fly at Mach 0.78 on FL370 (more common FL and spd used on the use case flow), without any conflicts and route modifications.
- No ATC restrictions applied on the routes.
- Perfect weather conditions.
- FF save 3.03%.

The simulation scenario under nominal conditions is based on traffic data from the AIRAC. Only flights operated by B738 aircraft that could be candidates for FF within the AS are simulated, following the routes and altitudes of the actual flown traffic. For the AS scenario, two aircraft are simulated using each of the calculated AS, flying at Mach 0.78 and FL370.

Once the simulations were completed, the following results were obtained. For the baseline scenario (SCN0), an average fuel flow of 2.758 kg/nm was observed. In contrast, for traffic using the AS (SCN1), the average fuel flow was 2.708 kg/nm, representing a 1.85% reduction in fuel consumption. This reduction is attributed to the ability to fly at a higher flight level while maintaining a constant altitude and speed during the cruise phase.

It should be noted that the results depend directly on the aircraft type, as well as the weight and speed used in these simulations. Values may vary depending on aircraft type, weather conditions, and performance parameters. Therefore, the results presented here represent this specific use case with the selected conditions and variables.

By applying Eq. (1) to calculate BDR\_dist, as described in Section 3.4 of the Methodology, the following result is obtained:

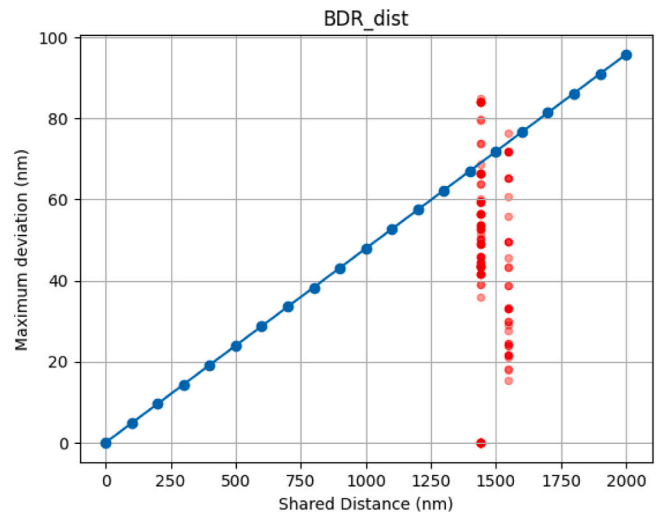


Fig. 19. BDR graph with example application.

Fig. 19 shows, in blue, the boundary representation of BDR by distance, taking into account the total shared distance and the maximum deviation an aircraft can make. As an example, the trajectories belonging to the flow between the Canary Islands, the United Kingdom, and Germany are shown in red. The BDR was calculated for all trajectory points within 90 nm of the AS entry points. The shared distance is assumed to be equal to the AS distance, as it is considered that the selected flow could use the AS in its entirety.

As can be observed, all points below the line designated by the BDR are likely to achieve fuel savings if they perform FF. Moreover, the

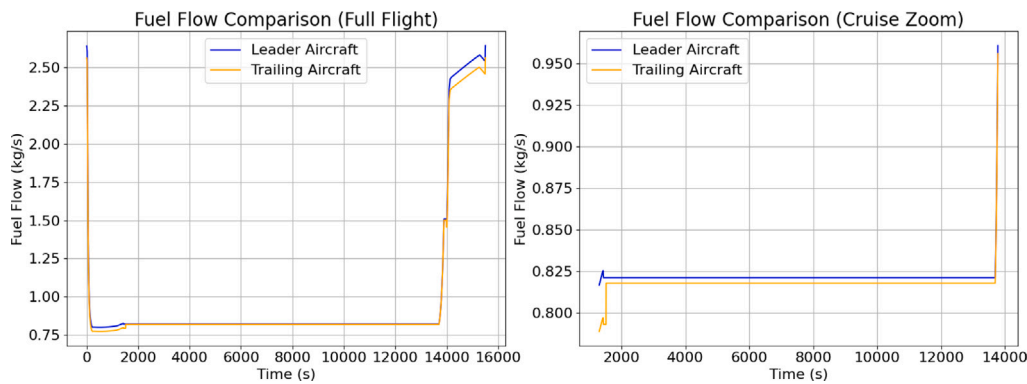


Fig. 20. RCF impact results.

further down a point is along the Y-axis, the greater the total benefit. This approach allows determination, for each trajectory, of the point that provides the maximum savings, in order to establish the optimal deviation toward the AS entry when a pairing is available for FF.

### 5.5. Reduced contingency fuel impact

Considering the results from Section 5.3.2, a total of 52 aircraft are estimated to have the potential to perform FF and utilize the AS. The estimation follows the methodology described in and is applied individually to each of the 52 identified aircraft for opportunistic FF.

For the simulation, an Initial Mass of 68 tonnes is assumed as the baseline for all aircraft. Of these 52 flights, 48 are B738s, 2 are A319s, and 2 are A320s. It is assumed that fuel savings during the formation-keeping phase amount to 3.03%. Two simulations are carried out with the same initial characteristics. RCF is applied only to the follower aircraft, thus allowing to reduce the Take Off Weight, and therefore, reducing the fuel consumption along all flight. This can be observed in the following graph:

In Fig. 20, an example of the calculation for the 52 simulated flights is shown. The orange line represents the flight with the RCF and FF coefficient applied, while the blue line represents the Baseline scenario without the RCF or FF coefficient applied. It can be observed that the largest difference in fuel flow occurs during the climb and descent phases. However, as seen in the graph on the right, there are also savings during the cruise phase. This savings will be accounted for the following FF savings estimation.

Assuming the ratio 1 kg of burned fuel produces 3.16 kg of CO<sub>2</sub>, as reported by Eurocontrol and ICAO in EUROCONTROL; SESAR Joint Undertaking (2019), International Civil Aviation Organization (ICAO) (2024), the results indicate an average savings of 169 kg of fuel per flight, corresponding to 534.04 kg of CO<sub>2</sub> when FF and RCF is performed. Considering that the savings only affect the trailing aircraft, half of the flights, 26 aircraft in total, will benefit from these savings. This corresponds to a total daily saving of 8.79 tonnes of fuel and 27.77 tonnes of CO<sub>2</sub> if all 52 aircraft perform FF. Assuming these 52 aircraft remain consistent throughout the year and operate under optimal flight conditions, the annual savings could potentially reach 1604 tonnes of fuel and 5070 tonnes of CO<sub>2</sub>. With the results obtained in this study, a B737 flying between the Canary Islands and northern Europe flies an average of about 1839 nm as shown in Fig. 5, assuming the fuel consumption per nm mentioned in Section 5.4 (2.758 kg/nm). This represents an average consumption of 5071 tonnes of fuel under standard operations. Considering a fuel saving of 169 kg per flight under RCF and FF operational conditions, a single aircraft flying twice a day the route could potentially save 123 tonnes of fuel and 389 tonnes of CO<sub>2</sub> annually.

## 6. Discussion

As mentioned in this article, the combination of AS and FF has never been evaluated, nor has its implementation in a use case. Furthermore, considering the barriers for the implementation of FF in Continental airspace, this paper highlight the design of AS as an excellent enabler for its future deployment. The results reveal distinct main traffic flows in Europe. The flow between the Canary Islands, Germany, and the United Kingdom shows significant potential due to its high traffic volume, the similarity of the routes used, and the distance of these flights. This creates a favorable environment for the implementation of AS and the use of FF.

Fuel consumption is a factor sensitive to many variables such as FL, speed, aircraft type, or fuel load. In this study, the majority of aircraft and the types of routes correspond to medium and short-haul flights. This means that the take-off mass is lower than on long-haul flights, so overall fuel consumption calculated is lower compared to a long-haul flights traffic flow.

Traffic analysis indicates that a substantial portion of current traffic holds strong potential for future research. Potential fuel savings and reductions in pollutant emissions could benefit both European and global environmental policies. Furthermore, the scalability and the number of aircraft that could take advantage of AS and FF could be increased through airspace planning and structuring that takes these methodologies into account.

This article proposes a new approach to integrate FF and AS, which have thus far been studied independently in two different European projects (European Commission, 2023a,b), but not the combination.

### 6.1. Limitations

This study presents the following limitation to be considered for its replicability and future improvement and work.

- The AS design methodology presented in this paper, requires an analysis of the main daily traffic flows, thus, the results described corresponds to the traffic analyzed and should be computed for each planned traffic in order to maximize the benefits of AS.
- Favorable weather conditions have been assumed for the traffic flow analysis. The impact of weather restrictions in sectors nearby the AS affecting traffic flow distribution would require the AS design and positioning with the new traffic flows. The dynamic aspect of weather restrictions is out of the scope of the analysis described in this paper.
- The impact of planned airspace restrictions or anticipated capacity regulations could be considered in the AS methodology by analyzing the new traffic flows.
- AIRAC files do not provide aircraft speed data, thus, the analysis has been performed by estimating the aircraft speed considering the time stamp at waypoints reported in AIRAC files.

- Fuel savings are highly sensible to operational environmental conditions and aircraft configuration, results might change depending on the Aircraft type or weather conditions. For the use case presented in this paper, an average FF saving has been considered in the simulation model.

## 6.2. Future work

For the continuation of this study, the following points will be evaluated:

- Identification of new flows within continental airspace for the implementation of AS.
- Assess if impact on intercontinental flights, using tracks as Air Streams, and operated by heavy weight aircraft, increases.
- Real-time evaluation of external conditions (weather and restrictions) for dynamic AS upgrade.
- Establishment of a trade-off to assess the cost of applying RCF, taking into account the probability of pairing.

## 7. Conclusions

This paper presents an ATM strategy for traffic management within European airspace, enabling opportunistic FF through the use of AS as a means to resolve en-route conflicts. The method is based on traffic data analysis using the DBSCAN clustering algorithm to determine AS and their positioning. Through this traffic analysis, an estimation is made of the number of flights with the potential to use AS and to perform FF. The results are illustrated through a case study of the flow between the Canary Islands, Germany, and the United Kingdom. Finally, the potential environmental impact and fuel savings associated with the use of AS in this use case are analyzed. The key conclusions of the paper are summarized as follows:

- Continental airspace presents great potential for the implementation of AS to support opportunistic FF. Almost 2% of all European daily traffic could potentially use the AS. A 9.28% of aircraft that use the AS could benefit of an important fuel reduction through opportunistic FF. Considering the probability of pairing candidates in the designed AS, and it is estimated that more than 18000 flights could benefit from the AS and FF annually.
- The implementation of FF and AS could represent a significant reduction in fuel waste and CO<sub>2</sub> emissions. The study accounts saving of 1600 tonnes of fuel and 800 tonnes of CO<sub>2</sub>, only from 52 daily FF.
- The use of AS by FF presents also operational and safety advantages for this strategy, as it reduces en-route complexity. The probability of pairing for FF could increase if other pre-flight measures are applied. Such as coordination on planned departure times and airport departure prioritization.
- It is of great importance to evaluate the trade-offs involved in the use of AS and FF, so that pairing and usage can ensure a common benefit for airspace users, both economically and environmentally.

## CRedit authorship contribution statement

**Oriol Bracons Escarré:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation. **Christian Eduardo Verdonk Gallego:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Miquel Angel Piera Eroles:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

The data that has been used is confidential.

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