SESAR Engage KTN – catalyst fund project final technical report

Project title:	Flight Centric ATC with Airstreams ('FC2A')
Coordinator:	NeoMetSys (NMS)
Consortium partners:	Ecole Nationale de l'Aviation Civil (ENAC)
Thematic challenge:	TC2 Data-driven trajectory prediction
Edition date:	30 November 2021
Edition:	1.1
Dissemination level:	Public
Authors:	D. Dohy / NMS
	F. Mora-Camino / NMS
	G. Mykoniatis / ENAC
	J-L. Raoul / NMS

This project has received funding from the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 783287.

Table of Content

1. Abstract and executive summary

1.1 Abstract

The project addresses a challenging approach for an environmentally friendly and more agile ATM framework by combining a Flight Centric ATC (FCA) approach and the Airstream concept. The day-to-day adaptation of the Airstream network to the demand of the airspace users will provide a resilient and scalable system for supporting Dynamic Airspace Configuration (DAC). Driven by the digitalisation of ATM, autonomous management of aircraft inside the Airstream is promoted.

A computational framework is implemented for the evaluation of the concept. New aggregation methodologies are proposed for extracting main traffic flows (aggregated flights) from the initial demand. A simple mechanism for building the tri-dimensional structure of the Airstream network and flight allocation is then applied using the aggregation results. New trajectories of the Airstream network traffic are ultimately produced. Finally, comparison of the various traffic samples (i.e. original versus airstream) is performed through complexity evaluation. The metrics used, based on geometric information approach, have been improved for large spherical areas.

1.2 Executive summary

Air traffic is currently facing a shift of paradigm due to changes in consumers' behaviour. The drop of air traffic in the last months is going to exhibit a slow recovery after the pandemic crisis ends while environmental concerns are gaining increasing importance [1]. Recent reports from ICAO [2] and ACI highlighted that recovery from the crisis will not occur unless the evolution of the demand and the customer confidence in the means of transportation are taken into account [3] [4]. More than ever, a reliable, safe, environment friendly and agile air transportation system, should be put in place. To address future challenges, an optimal use of resources is mandatory and can be achieved by dynamically fine-tuning the capacity of Air Navigation Service Providers (ANSP) according to the fluctuation of the demand. Within this frame, a new concept using flows to organize the air traffic emerged and aims at delegating some of the operations tasks to aircraft. It is pushed through the project Flight Centric Air Traffic Control with Airstreams (FC2A), funded by SESAR, whose final goal is to satisfy the initial demand of airlines to fly the most direct trajectory between city pairs while avoiding the high traffic complexity inherent to pure free flight. In this ongoing work, parallel flight lanes are created within a larger tubular volume thus creating a highway-like structure. Due to the high level of organization, complexity is significantly low within such a tube, allowing a denser traffic. The medial axis is found using a clustering procedure that extract major flows of traffic and is the most representative flown trajectory within a set of samples. It can be adjusted on the fly to cope with a structural change. To assess the performance of the FC2A concept of operations, both airline oriented KPI and complexity must be considered. While indicators pertaining to the first class are quite well known, the second one is still an area of active research and has several facets. It can be related to workload, which is a perception of a given situation by a human controller or to disorder, which is intrinsic.

In this context, FC2A project has developed two bundling approaches for clustering the traffic in order to extract and identify major flows.

The first one is to use the trajectories (an ordered list of timestamped positions) and is based on the k-medoids clustering algorithm. This algorithm is robust with respect to outliers. Furthermore, for each cluster, the central element is a member of the aggregate, thus it is always flyable in an operational context.

The second one is to consider city pairs. Considering there is no difference of treatment between flights of different airlines flying between the same airports, the focus is given here on Air-Links (direct path between each pair of considered airports) rather than in individual flights.

The goal of these bundling mechanism is to partition the traffic into groups/aggregates as homogeneous as possible and separated one to another as much as possible. The flight aggregates then define the backbone (main flows) of the so-called Airstream network. Each cluster is allocated to an Airstream which is built using the intrinsic characteristics of the aggregated traffic.

A first set of rules are proposed to build the tri-dimensional structure of an Airstream. The main characteristics selected are the cruise flight level and the speed. The distribution of speed throughout the complete sample allows to define Speed Families (SF) which are used to build the longitudinal (i.e horizontal) structure of an Airstream. The vertical structure is built using the vertical levels found in the aggregate. A first set of elementary rules are applied on the aggregate, for building the final vertical structure of an Airstream. These rules consider the global schema of the network such as crossings and define free flight levels to allow smooth management of these crossings.

The first results of the project are promising, as the actual amount of traffic allocated to the Airstream network represents the lower limit of the concept, due to the hypotheses used. There is potential improvement of the methodology for defining the tri-dimensional structure of the Airstream and the allocation of traffic which should allow to reach the expected ratio of 60 to 70%.

Finally, the flight trajectories are re-calculated for the traffic allocated to the Airstream network.

The project has developed a complexity calculation by enhancing a method based on local linear models and a representation of traffic situations as images whose pixels are covariance matrices. This algorithm has been improved to be used on larger areas by extending the model on the sphere, using stereographic projection. The evaluations done on the samples show a potential decrease of 30 to 40% of the structural complexity of the traffic with the introduction of an Airstream network in the European airspace.

2. Overview of catalyst project

2.1 Operational/technical context

After an initial communication in 1999, the European Commission started in 2004 the first Single European Sky (SES-I) legislation in order to overcome the fragmentation of its airspace, by structuring space and navigation services at a European level. Under the umbrella of SES-I, the Single European Sky ATM Research programme (SESAR) is launched in 2004. A similar modernisation program has been launched in the United States (NextGen). Among new concepts, Trajectory Based Operations (TBO) supported by the digitalisation of the air transport system opened new perspectives to optimise air traffic management.

European airspace geographical fragmentation has been put in place to provide safe services for aircraft travelling through the airspace but has a negative impact on airspace capacity. A flight-centric approach opens the opportunity to distribute the traffic more evenly. Furthermore, it would prevent productivity loss in under-loaded sectors. This approach is coupled with the design of dynamically allocated flow corridors: the Airstreams. When flying within the airstream, an aircraft has an intrinsically low interference with all other traffic, whether it is in the same direction, opposite direction or crossing traffic.

Three of the prominent attributes of these flow structures that would distinguish them from today's airways are:

- Allowance for multiple (parallel) lanes of traffic;
- Capitalization on advanced communication, navigation, and surveillance technologies to enable changes in methods of separation (e.g. self-separation), potentially reduced separation standards within the Airstream;
- Dynamic activation rules to add or remove corridor structures, as needed, throughout the day.

2.2 Project scope and objectives

The study of specific airspace organization dedicated to traffic sharing similar flying characteristics and/or decreasing complexity and ATCO workload has been widely explored since decades. They have been called highways [5] [6], Freeways [7] [8], High Volume Tube-Shape sectors (HTS) [9] corridors [10] [11]. The concept proposed here intent to organize flights using a flight centric approach defining space-based slots and local indexed axial coordinates system to reference the aircraft along common 3-dimensional reference trajectory. These structures are called Airstreams.

An airstream has no nominal shape (width, height, or radius). In some situations, the central line of an airway could be adopted as the main axis: the AirStream Reference Track (ASRT). Although Airstream reference trajectories may present turns and may be adapted according to different factors such as traffic demand and next day forecasted weather conditions.

The scope of FC2A project is to demonstrate whether Flight Centric ATC with Airstreams is a promising candidate to be incorporated into the emerging Dynamic Airspace Configuration management.

The main objectives of the project are to:

- Assess the amount of traffic captured by Airstreams for complementing and supporting the free route and dynamic airspace configuration approaches;
- Define initial characteristics of the Airstream structure to cope with the constraints of the European Airspace and traffic demand;
- Assess whether traffic structural complexity is reduced due to the introduction of Airstreams.

To be able to achieve these, the following research questions are identified:

- ***Q. 1***: How to group flights into major flows?
- ***Q. 2:*** What kind of traffic is targeted?
- ***Q. 3:*** What is the amount of traffic to be managed by the Airstream network?
- ***Q. 4:*** What are the main characteristics of the Airstream structure?
- ***Q. 5***: How to evaluate the complexity?
- ***Q. 6***: Is the structural complexity decreased with the use of Airstreams?

To have feedbacks and advice from the community about ***Q. 2*** - ***Q. 4***, two workshops (one on operational aspects and one on technical aspects) have been organised.

2.2.1 Flow management in high density/complexity areas

The Airstream is organised around its ASRT. Its skeleton, or axis, is a smooth curve selected so as to best represent the mean path followed by aircraft in its vicinity [12]. Aircraft with different performances, cost indexes and speeds can be present in the same Airstream but are segregated along different lanes. The lanes are surrounding the ASRT, a peripheral lane is specifically dedicated for the traffic entering or exiting the Airstream as described in Figure 1.

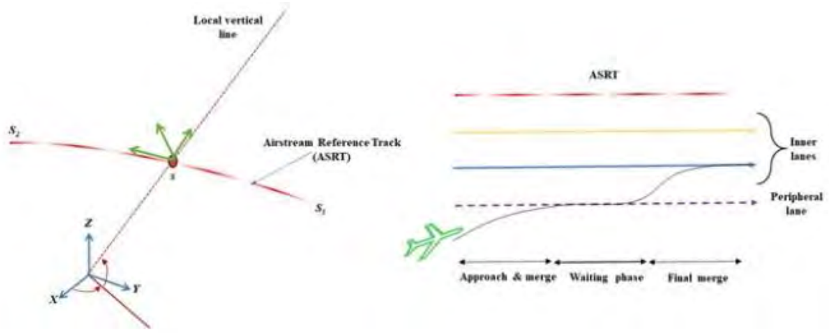


Figure 1 Airstream Reference Track and traffic lanes

The main challenge is to determine what are the various flows which can be eligible for the definition of an Airstream structure. It is then necessary to develop methods for building these main axes using aggregation mechanisms. This activity is linked to ***Q. 1*** and ***Q. 2***.

2.2.2 Characteristics of the Airstream network

Inside the Airstream, traffic separation is delegated to crews or automatic on-board systems. It implies that all aircraft must comply with required navigation performance (RNP) and, be equipped with means for providing the separation service. Self-separation on a lane can be performed by dynamic position adjustments (ADS-B technology for instance) [13]. The pilots will remain responsible for ensuring safety norms with nearby aircraft by maintaining situational awareness, performing standard manoeuvres and reacting to conflict resolution advices.

Time slots allocated to aircraft are translated into spatial slots. Each aircraft is supposed to remain in the centre of its dedicated spatial slot when moving along a lane. This centre is a permanent target for its guidance system. The lanes are defined for serving a homogeneous traffic mainly driven by the aircraft performances. Except for the integration phase and the extraction phase, the aircraft will be assigned to a specific lane when in the Airstream. However, changing lane either vertically or horizontally, remains possible thanks to specific traffic conditions. To allow these manoeuvres, the characteristics (e.g. speed interval) of adjacent lanes are overlapping, and free slots will be available to facilitate path changes. This mechanism is presented in Figure 2.

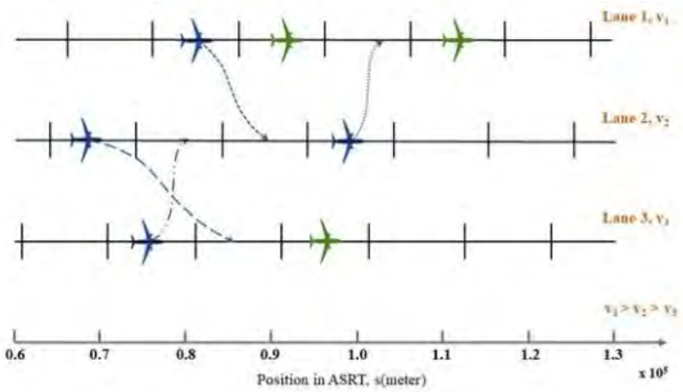


Figure 2 Aircraft changing lanes in an Airstream

The primary characteristics used for defining a lane is a flight level and a speed interval. To cope with the Airstream regulation, only aircraft whose performances are compatible with this speed interval can be allocated to the lane. It can be checked using data such as the BADA performance tables to verify the compliance with the characteristics of a lane.

During this study, the structure of the Airstream is dynamically calculated based on the traffic allocated to it. However, various parameters and/or rules can be applied to generate the tri-dimensional structure of the Airstream (***Q. 3*** and ***Q. 4***). These parameters are tuned thanks to the outcomes from the two workshops conducted during the project. Main outcomes are summarised in Annex III (§ 8).

2.2.3 Complexity evaluation

Traffic complexity has been a driver for the design of the controlled airspace, however there is no consensus to date on which traffic complexity metric to adopt, so it appears opportune to design an Airstream structure independently of the adopted traffic complexity metric.

The various complexity approaches have to be explored in order to select the appropriate one for the project (***Q. 5***).

Once this Airstream tri-dimensional structure is defined, it becomes possible to assess, according to complexity measures, the performance improvement resulting from the assignment of parts of flights to the Airstreams network (***Q. 6***).

2.3 Research carried out

In order to address the 6 research questions (§2.2), a framework has been defined based on 2 main components:

- An experimental environment, based on a "spin-off" of the π-rats tool from Ecole Nationale de l'Aviation Civil (ENAC);
- A stakeholder survey structured around two workshops.

The data flow is presented in Figure 3. It allows to agree on targets and federates the various work-packages.

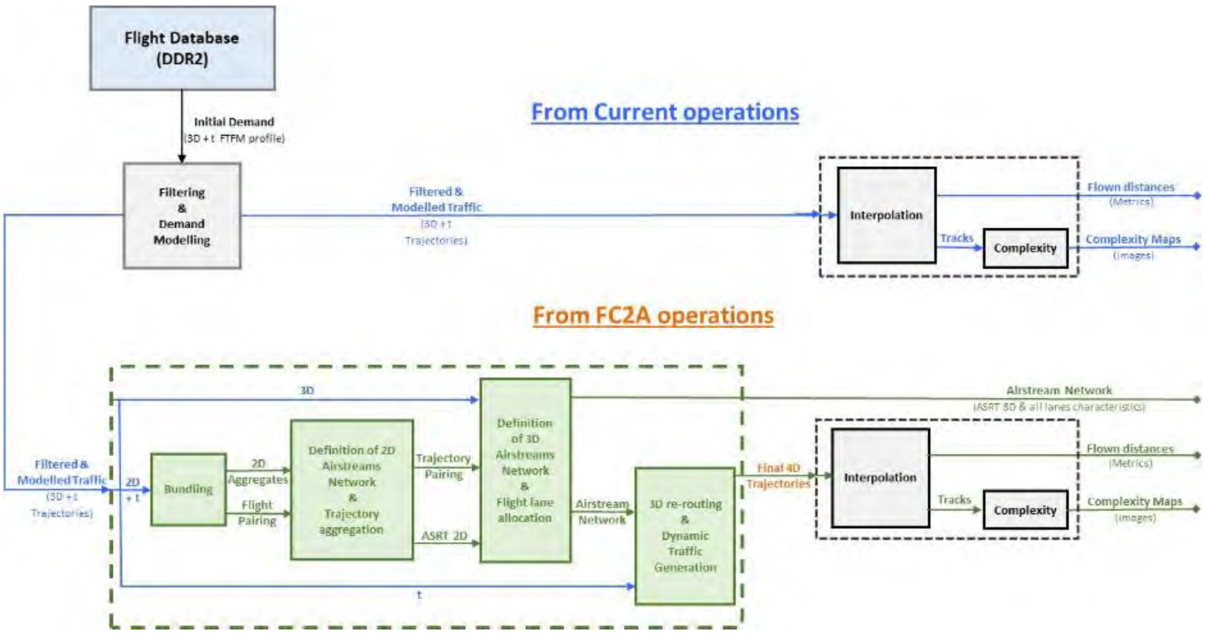


Figure 3 FC2A Data Flow

Input data have been selected from 2019 daily records, as the most representative samples of traffic of the pre-COVID pandemic. To evaluate the Airstream impact on different patterns of traffic the EUROCONTROL report on the daily traffic over Europe (Figure 4) was used. Three scenarios are considered ranked by traffic density (low, medium & high). For each pattern, a weekday and a weekend day are allocated leading to the selection of six traffic samples.

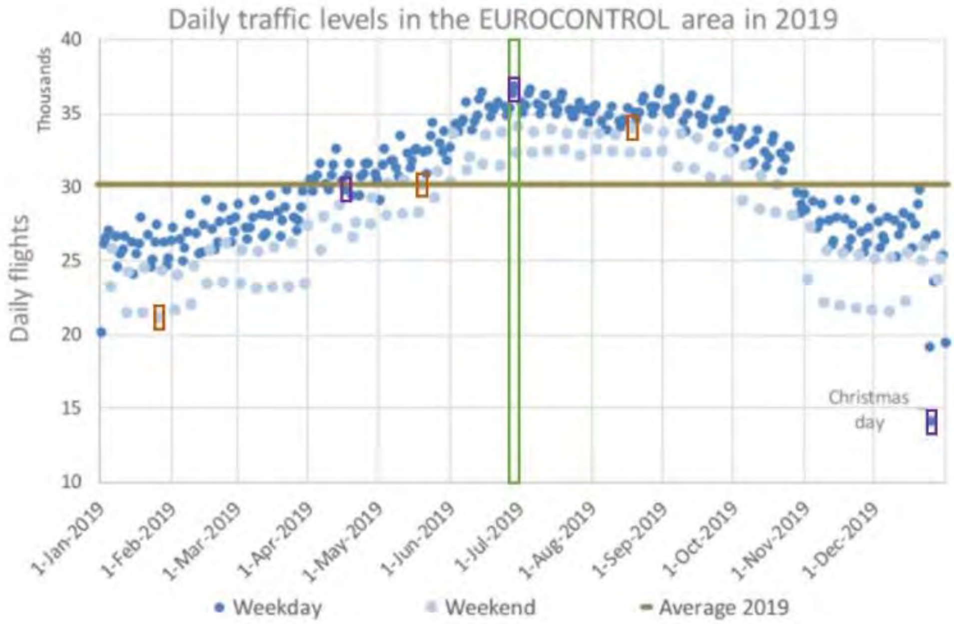


Figure 4 Selected days from the EUROCONTROL report on daily traffic

The samples are extracted from the DDR2 database and are "pre-processed" before being used. The so-called filtering process of the input data (ALL_FT+) is based on five characteristics of a flight:

- Flight departing or arriving from "ZZZZ" or "AFIL";
- Loop flights (same arrival and departure airport);
- Flights with a requested flight level (RFL) below a threshold (parameter);
- Flights that do not enter the ECAC[1] airspace;
- Flights that have a "limited" flight time in the ECAC airspace (parameter).

If at least one of these criteria applies to a flight, this flight is filtered (i.e. removed). For more details and examples refer to § 9.

2.3.1 Simulation algorithms

2.3.1.1 Medoid clustering

2.3.1.1.1 Distance between trajectories

Having at hand a measure of similarity between any two trajectories is mandatory to process the traffic data. A distance is such a measure, with some extra requirements. From an axiomatic standpoint, a distance on an abstract set E is a mapping $d: E \times E \rightarrow R^{+}$ such that:

$$\begin{cases} d(x,y) = 0 \Leftrightarrow x = y \\ d(x,y) = d(y,x) \\ d(x,z) \leq d(x,y) + d(y,z) \end{cases} \qquad \textit{Eq. 1}$$

The last axiom is known as the triangle inequality and is often needed in clustering algorithms. For air traffic applications, the elements of the set E are functions, making the problem of finding relevant distances more difficult that in the case of finite dimensional vector spaces.

[1] Some EUROCONTROL members are not part of the ECAC.

One the most widely used distance for R^d valued functions defined on a common real interval $[a,b]$ is the so-called L^2distance. It is based on an inner product:

$$\langle f,g\rangle_{L^2} = \int_{[a,b]}\langle f(t),g(t)\rangle dt \qquad \textit{Eq. 2}$$

A function f for which $\langle f,f\rangle_{L^2} < +\infty$ is said to be square integrable and the set of such functions is denoted by $L^2([a,b])$. It is an inner product vector space, with norm $\|f\| = \sqrt{\langle f,f\rangle_{L^2}}$ and distance $d(f,g) = \|f-g\|$. While quite appealing due to its particularly good theoretical properties and ease of computation, this distance has several flaws:

- All functions must be defined on a common interval. It is not the case in the air traffic application as trajectories have different departure and arrival times.
- It is sensitive to a change in parameterization. When comparing trajectories, it means that paths with similar shapes but flown at different speeds will considered to be different. It is clearly a drawback for finding airstreams central lanes.
- Trajectories with quite different shapes and trajectories that are just translated may be at the same distance, which is not relevant in an operational context.

The third point can be delt with by adding a term based on the speed (or even higher derivatives) in the expression of the distance. In general, if *L* is a differential operator, a distance can be constructed from the next inner product:

$$\langle f,g\rangle_{H^2} = \int_{[a,b]}\langle f(t),g(t)\rangle + \langle Lf(t),Lg(t)\rangle\, dt \qquad \textit{Eq. 3}$$

The space of functions for which the above expression is defined is called a Sobolev space, denoted by H^2 (the differential operator *L* is implicit). With the Sobolev distance, the difference in speed orientations or curvatures along trajectories can be considered, thus allowing morphological features to be included.

The second point is unfortunately very difficult to solve and requires an amount of computation incompatible with the analysis of large datasets. Most of the time, only an approximate solution is sought after, and it is the way it was addressed in the project. It turns out that the procedure used solve also the first point.

The first step for distance computation is to perform a reparameterization by arclength. Given a trajectory γ: $[a,b] \rightarrow R^3$, the arclength at $t \in [a,b]$ is:

$$s(t) = \int_a^t \|\dot{\gamma}(u)\| du \qquad \textit{Eq. 4}$$

Since *s* is a strictly increasing mapping, it can be inverted. Let $t(s)$ be the value of the inverse mapping at arclength *s*. The original trajectory may be parameterized on the interval [0,1] as:

$$\tilde{\gamma}(u) = \gamma(a + t(s(1).u)) \qquad \textit{Eq. 5}$$

Using this simple transformation, the Sobolev distance can be computed and in the Airstream application, only the first and second derivatives of the trajectories are used.

2.3.1.1.2 Clustering algorithm

Clustering is a well-known statistical procedure aiming at grouping data by similar features. Formally, it is a random variable *Z* mapping values in the observation space to a finite set $(z_1, \dots, z_p)$ whose elements are interpreted as labels for the data. Given a sample $(x_1, \dots, x_N)$, the cluster with label $z_k, k = 1, \dots, p$ is the set $C_k = \{x_i, Z(x_i) = z_k\}$ or, more intuitively, the observations labelled with z_k. From the definition, it is clear that the set of clusters form a partition of the dataset.

A clustering algorithm tries to obtain the function Z minimizing a dispersion criterion. A quite common one when the data belong to a normed space is the intra-class inertia, defined as:

$$I = \sum_{k=1}^{p} \frac{1}{2\#C_k} \sum_{x_i \in C_k, x_j \in C_k} \left\| x_i - x_j \right\|^2 \qquad \textit{Eq. 6}$$

Obtaining the best possible clustering is a difficult task, proved to pertain to the class of NP problems, but locally optimal solutions are often good enough for practical use. For the above criterion, the celebrated k-means algorithm proceeds in an iterative way, improving *I* at each step. Its pseudo-code is given below.

1 - Randomly select cluster centres $\mu_1, \dots, \mu_p$ in the observation space *E*.
2 - Label each sample by its closest centre index, yielding a clustering $C_k, k = 1, \dots, p$.
3 - Set centres to inter-cluster empirical mean:

$$\mu_k = \frac{1}{\#C_k} \sum_{x_i \in C_k} x_i \qquad \textit{Eq. 7}$$

4 - Iterate at step 2 until the centres variation is small enough.

As classical with means-based algorithms, sensitivity to outliers is a drawback of this algorithm and may limit its effectiveness. A more robust one is the so-called k-medoids, which has also the distinguished feature of having samples as cluster centres. This fact is of particular interest when the computation of an empirical mean is difficult or time consuming, but also when the mean itself may fail to belong to the set of observations. In the case of air traffic analysis, this last point is critical as an empirical mean of trajectories may yield to a non-flyable curve.
Instead of using a gradient descent, the k-medoids algorithm works by swapping samples to improve the dispersion criterion:

1 - Randomly select medoids $m_1, \dots, m_p$ from the dataset.
2 - Assign all samples to the cluster labelled by the closest medoid.
3 - For all non-medoid x_i and medoid m_j, try to swap them and evaluate the cost. Keep the best possible move.
4 - Iterate to step 2 until no swap is performed.

For large datasets, an exhaustive testing of all possible moves is not possible, and some special strategies must be used. The algorithm CLARA [14]and its variations proceeds by performing parallel clustering on subsets of the whole dataset and keeping the best one. It has proved quite efficient on test situations with trajectories as data and was selected for finding the central lane of the Airstreams.
A completely different approach to the clustering problem is to estimate data density and select its modes as cluster centres. This is the principle underlying DBSCAN algorithm and its relative, where a cheap estimate of the density is obtained from the volume of the ball enclosing the k-th nearest neighbours of a point. For functional data, like in the case of aircraft trajectories, a pre-processing step must be added in order to project samples to a finite dimensional vector space. The choice of the expansion basis and the truncation order of the series expansion is quite critical and limits in practice the effectiveness of this family of algorithms.

2.3.1.2 Air-Link clustering

Besides the medoid clustering, a second approach has been evaluated. This approach considers that the ultimate desire of airlines would be to deliver more direct flights between departure and arrival airports so that travel distances and durations are minimum, optimizing the transportation service offered to costumers, contributing to the minimization of operational costs and to a more efficient aircraft fleet management.

As seen above, this has led to the concept of free flight where the planned 3D+T aircraft trajectory is computed according to the geographical position of the departure and arrival airports, the performances of the operated aircraft, weather forecast (mainly winds) along the flight, timing constraints and overfly restrictions. Then, the direct path (in some way minimum cost) trajectory for a flight is smooth but do not follow in general a great circle segment in its cruise part as would do a direct flight.
At the stage of carrying out these free-flights, the blind superposition of such types of trajectories leads to the generation of potential conflicts which need the intervention of traffic control to prevent their realization, de-characterizing the computed free-flight trajectories.
This situation contributes to increase the complexity of air traffic and limit its performance (diminished capacity, new delays, extra costs, and increased risk).
Figure 5 illustrate in 3D desired, planned, and effective trajectories of a flight.

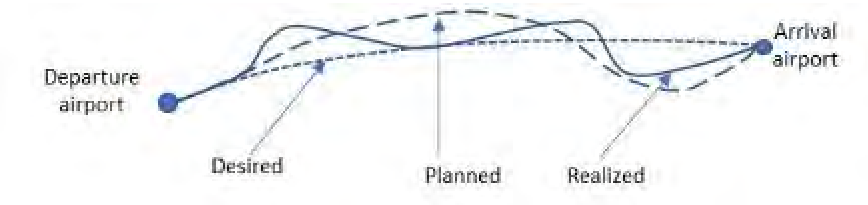


Figure 5 Desired, planned and realized flight trajectories

Planned trajectories are given by the flight plans filed by the airlines to ATFM. Both planned (FTFM) and realized (RTFM) trajectories can be extracted from the DDR2 data base, while desired is represented by the orthodromic path.
Considering that from the point of view of Air Traffic Control, there is no difference of treatment between flights of different airlines realized between the same airports, the focus is given here on Air-Links between each pair of considered airports, rather than in individual flights.
An Air-Link will be characterized by:

- The pair of arrival and destination airports (no order);
- The free flight trajectory between them and its length;
- The number of flights using this Air-Link during a day period.

Then, the number of Air-Links is much smaller than the number of flights, limiting already the computational burden.

2.3.1.2.1 Solution approach

A solution approach which limits this difficulty is developed in three steps:

- First by considering Air-Links between airports rather than flights;
- Second by designing a heuristic algorithm which processes sequentially the Air-Links to build clusters;
- Third by positioning for each cluster the position of a candidate Airstream.

The direct flight trajectory is associated to the orthodromic curve between two airports a_p and a_c. It is characterized by its mean Route Ra_pa_c and Root Pa_pa_c (see figure below).

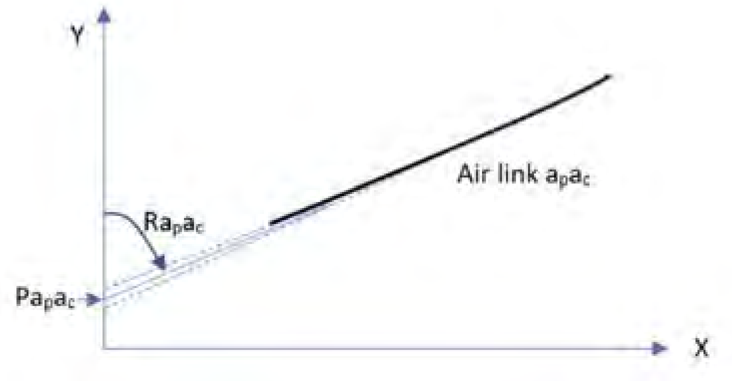


Figure 6 Orthodromic segment parametrization

with

$$Ra_pa_c = \frac{1}{2}\left(arcotan\left(\frac{cos\,(lat_{ap}).tg\,(lat_{ac})}{sin\,(lon_{ac}\text{-}lon_{ap})} - \frac{sin\,(lat_{ap})}{tg\,(lon_{ac}\text{-}lon_{ap})}\right) + arcotan\left(\frac{cos\,(lat_{ap}).tg\,(lat_{ac})}{sin\,(lon_{ac}-lon_{ap})} - \frac{sin\,(lat_{ap})}{tg(lon_{ac}-lon_{ap})}\right)\right) \quad Eq.\ 8$$

and

$$Pa_pa_c = \frac{1}{2}\left((Ya_c - cotg\,(Ra_pa_c).\,Xa_c) + (Ya_p - cotg\,(Ra_pa_c).\,Xa_p)\right) \qquad Eq.\ 9$$

2.3.1.2.2 Clustering approach

The clustering approach which progressively builds each cluster by inspection of the Air-Link list and on-line adaptation is described below. This method applied to the Air-Link set in a sequential way should reduce the computational burden compared with for example optimizing approaches or global approaches. Two parameters can be tuned for generating the clustering:

- The Maximum route deviation: ε (angle in radians);
- The Maximum root deviation: $drelmax$ (relative distance extension in percentage).

Steps of heuristic are:

1 - Rank Air-Link by traffic volume;
2 - Select the first one as a seed for the first cluster and Airstream;
3 - Compare routes then roots and gather or not in the current cluster;
4 - Update Airstream and check next Air-Link;
5 - If all Air-Links have been checked and no more Air-Links, search ends;
6 - Otherwise create a new cluster and Airstream and start again with remaining Air-Links.

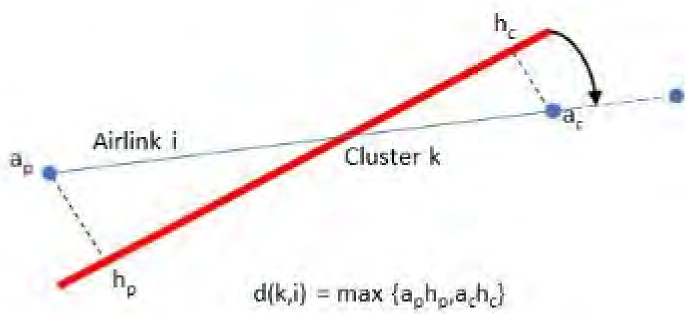


Figure 7 Air-Link positioning with respect to cluster

2.3.1.2.3 Defining candidate Airstreams associated to clusters

The European airspace is considered on a planar representation with cartesian coordinates centered at Prague Airport position (50.1018°N, 14.2632°E). The direct flights and Air-Links are represented by linear segments. This results for the Airstream generation process in computations of low complexity following Euclidian geometry.

Let N_c be the number of clusters generated by the clustering process and let N_{FC} be the number of flights in cluster C, C = 1 to N_C.

Let i be the i^{th} flight in cluster C,

- Get x_i^D, y_i^D , the coordinates of the departure airport of flight i and get x_i^A, y_i^A the coordinates of the arrival airport of flight i, from their longitude and latitude data;
- Get t_{Di} and t_{Ai} , the planned departure and arrival times of flight i of cluster C, given in minutes from 0 to 1440 (one day).

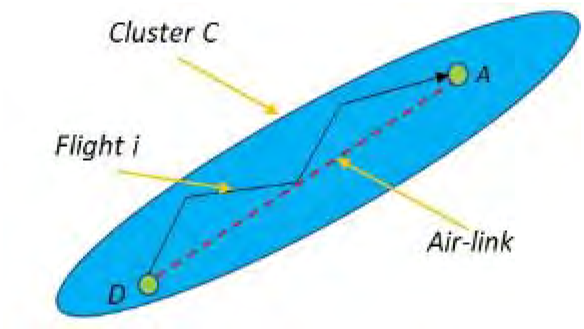


Figure 8 Air-Link in a cluster

2.3.1.2.4 Search space and initialization

The departure and arrival airports of Air-Link i are on the line of equation:

$$\alpha_i \cdot x + \beta_i \cdot y = 1 \qquad \text{Eq. 10}$$

With

$$\alpha_i = (y_i^A - y_i^D)/(x_i^D \cdot y_i^A - x_i^A \cdot y_i^D) \text{ and } \beta_i = (x_i^D - x_i^A)/(x_i^D \cdot y_i^A - x_i^A \cdot y_i^D) \qquad \text{Eq. 11}$$

It is assumed[2] that no flight line pass through the origin (0,0) so that: $x_i^D \cdot y_i^A - x_i^A \cdot y_i^D \neq 0$, if there is such a flight, it can be excluded from the above computations.

- Compute α_i, β_i
- Compute $\alpha_{XC} = \sum_{i=1}^{N_b} \alpha_i / N_{TC}$, $\beta_{YB} = \sum_{i=1}^{N_b} \beta_i / N_{TC}$
- Compute $a_C^{min} = \min_{i=1,\cdots,N_B} \alpha_i$, $a_B^{max} = \max_{i=1,\cdots,N_B} \alpha_i$
- Compute $b_C^{min} = \min_{i=1,\cdots,N_B} \beta_i$, $b_b^{max} = \max_{i=1,\cdots,N_B} \beta_i$

Let $L_i = \sqrt{(x_i^D - x_i^A)^2 + (y_i^D - y_i^A)^2}$ be the distance between the departure and arrival airports, assuming that a large part of the flight will be inside the Airstream, a measure of its interest for that flight is given by its length.

So, we get a possible guess of the position of the associated Airstream by bundling C by:

$$\alpha_C = \sum_{i=1}^{N_b} \alpha_i \cdot L_i / L_C \qquad \beta_C = \sum_{i=1}^{N_b} \beta_i \cdot L_i / L_C \qquad \text{with } L_C = \sum_{i=1}^{N_C} L_i \qquad \text{Eq. 12}$$

[2] If there is such a flight, it can be excluded from the above computations.

Two situations may arise, as shown in Figure 9.

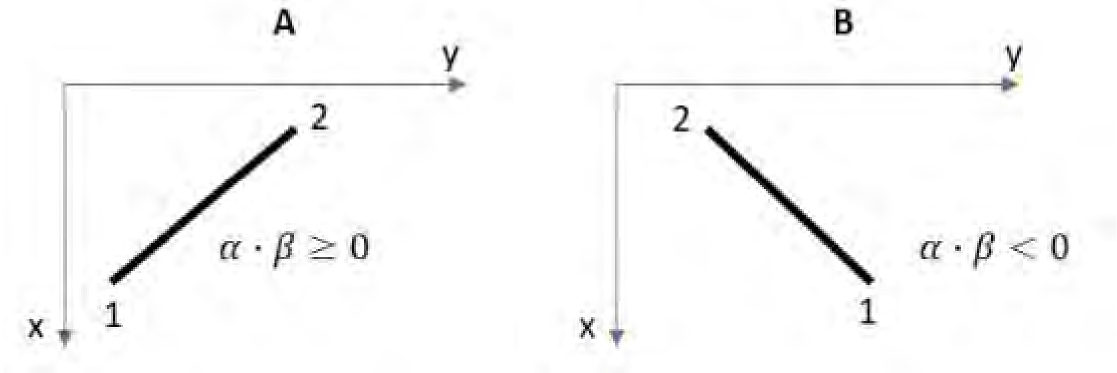


Figure 9 Two potential situations in searching Airstream position

The coordinates of the projections of departure and arrival airports on the Airstream line are given by:

$$x_{Hi}^{D} = \frac{\beta^2}{\alpha^2+\beta^2} \cdot x_i^D - \frac{\alpha \cdot \beta}{\alpha^2+\beta^2} \cdot y_i^D + \frac{\alpha}{\alpha^2+\beta^2} \quad \text{Eq. 13}$$

$$y_{Hi}^{D} = \frac{\alpha^2}{\alpha^2+\beta^2} \cdot y_i^D - \frac{\alpha \cdot \beta}{\alpha^2+\beta^2} \cdot x_i^D + \frac{\beta}{\alpha^2+\beta^2} \quad \text{Eq. 14}$$

$$x_{Hi}^{A} = \frac{\beta^2}{\alpha^2+\beta^2} \cdot x_i^A - \frac{\alpha \cdot \beta}{\alpha^2+\beta^2} \cdot y_i^A + \frac{\alpha}{\alpha^2+\beta^2} \quad \text{Eq. 15}$$

$$y_{Hi}^{A} = \frac{\alpha^2}{\alpha^2+\beta^2} \cdot y_i^A - \frac{\alpha \cdot \beta}{\alpha^2+\beta^2} \cdot x_i^A + \frac{\beta}{\alpha^2+\beta^2} \quad \text{Eq. 16}$$

The minimum and maximum values can be defined as:

$$x_i^{min} = \min\{x_{Hi}^D, x_{Hi}^A\} \qquad x_i^{max} = \max\{x_{Hi}^D, x_{Hi}^A\}$$

$$y_i^{min} = \min\{y_{Hi}^D, y_{Hi}^A\} \qquad y_i^{max} = \max\{y_{Hi}^D, y_{Hi}^A\}$$

The extreme limits of the Airstream can be evaluated:

Case **A:** $x_1^C = \max_{i=1,\dots,N_{FC}} \{x_i^{max}\}$ $\quad x_2^C = \min_{i=1,\dots,N_{FC}} \{x_i^{min}\}$ $\quad y_1^C = \min_{i=1,\dots,N_{FC}} \{y_i^{min}\}$ $\quad y_2^C = \max_{i=1,\dots,N_{FC}} \{y_i^{max}\}$

Case **B:** $x_1^C = \max_{i=1,\dots,N_{FC}} \{x_i^{max}\}$ $\quad x_2^C = \min_{i=1,\dots,N_{FC}} \{x_i^{min}\}$ $\quad y_1^C = \max_{i=1,\dots,N_{FC}} \{y_i^{max}\}$ $\quad y_2^C = \min_{i=1,\dots,N_{FC}} \{y_i^{min}\}$

The maximum length of Airstream *C* is given by:

$$\Lambda_C = \sqrt{(x_1^C - x_2^C)^2 + (y_1^C - y_2^C)^2} \quad \text{Eq. 17}$$

The maximum number of segments is N_C^S given by: $N_C^S = \left\lceil \frac{\Lambda_C}{\delta} \right\rceil$ where δ is set as shown Figure 10.

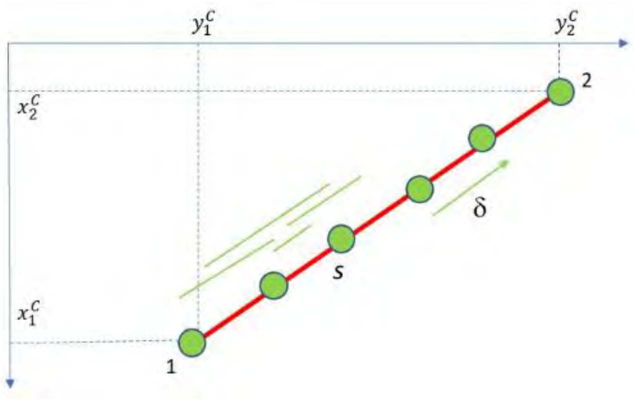


Figure 10 Maximum length of Airstream

The distance parameter δ has to be chosen, a good candidate is the minimum distance between two inputs/outputs of an airstream.

2.3.1.2.5 Computation of the potential load l_s of each segment *s*:

Considering $\delta_x = \delta \cdot (x_1^C - x_2^C)/\Lambda_B$, by traversing all the segments of the Airstream (1 to N_C^S) the load of each segment can be evaluated depending on x_i values:

- $x_1^C - (s-1) \cdot \delta_x \geq x_i^{max} > x_1^C - s \cdot \delta_x$ => $l_s = l_s + 1$;
- $x_1^C - (s-1) \cdot \delta_x \geq x_i^{min} > x_1^C - s \cdot \delta_x$ => $l_s = l_s + 1$;
- $x_1^C - (s-1) \cdot \delta_x \geq x_i^{min}, x_i^{max} > x_1^C - s \cdot \delta_x$=> $l_s = l_s - 1$;
- $x_1^C - s \cdot \delta_x > x_i^{min}$ and $x_i^{max} > x_1^C - (s-1) \cdot \delta_x$=> $l_s = l_s + 1$.

The spatial width of the Airstream with load over l_{min} *can be defined as follows:*

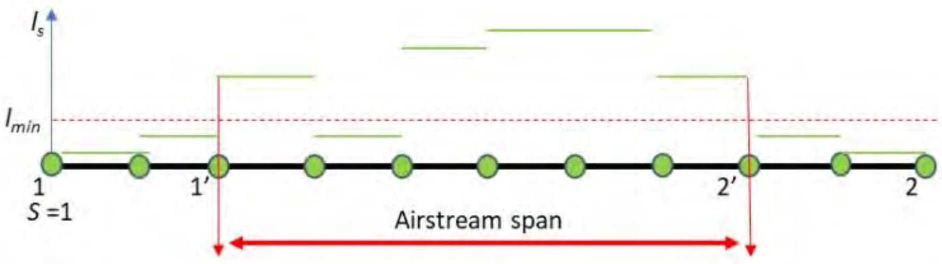


Figure 11 Load of the segments

$$s_{min} = \underset{s=1,\cdots,N_B^S}{argmin}\{l_s | l_s \geq l_{min}\} \qquad s_{max} = \underset{s=1,\cdots,N_B^S}{argmax}\{l_s | l_s \geq l_{min}\} \qquad \textit{Eq. 18}$$

Again, there are two cases as defined in Figure 9, for which δ_y is defined as:

Case **A** $\delta_y = \delta \cdot (y_2^C - y_1^C)/\Lambda_B$ Case **B** $\delta_y = \delta \cdot (y_1^C - y_2^C)/\Lambda_B$

Coordinates of the limits of Airstream C with respect to l_{min} are thus expressed by:

	$X_1^C = x_1^C - (s_{min} - 1) \cdot \delta_x$		$X_2^C = x_2^C - s_{max} \cdot \delta_x$
Case **A**:	$Y_1^C = y_1^C + (s_{min} - 1) \cdot \delta_y$	Case **A**:	$Y_2^C = y_2^C + s_{max} \cdot \delta_y$
Case **B**:	$Y_1^C = y_1^C + (s_{min} - 1) \cdot \delta_y$	Case **B**:	$Y_2^C = y_2^C - s_{max} \cdot \delta_y$

The length of the Airstream C is then expressed by:

$$L_C = (s_{max} - s_{min}) \cdot \delta \qquad s_i^C = s_{max} - s_{min} \qquad \textit{Eq. 19}$$

The Entry/Exit points have the following coordinates, considering m has a range from 1 to s_i^C:

$$X_m^{EC} = X_1^C - (m-1) \cdot \delta_x$$

Case **A**: $$Y_m^{EC} = Y_1^C + m \cdot \delta_y$$

Case **B**: $$Y_m^{EC} = Y_1^C - m \cdot \delta_y$$

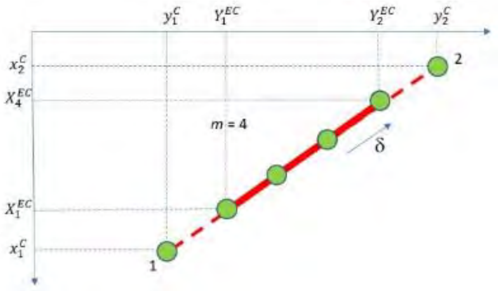


Figure 12 Evaluation of Entry and Exit points

Considering the temporal size of the Airstream, the following assumption is considered. A flight will only consider Airstreams which exist before their planned departure time and after their planned arrival time. Then a simple way to define the time window is:

$$T_C^1 = \min_{i=1,\cdots,N_{FC}} t_{Di} \qquad T_C^2 = \max_{i=1,\cdots,N_{FC}} t_{Ai} \qquad \text{with } C = 1 \text{ to } N_{TB} \qquad \text{Eq. 20}$$

2.3.1.3 Airstream tri-dimensional structure

To distribute the aggregated traffic evenly through the Airstream, it is necessary to define what are the main characteristics of a lane but also the global structure of the Airstream such as its longitudinal extension (i.e. the number of horizontal lanes at a given FL) and its vertical extension (i.e. the number of consecutive FLs). These characteristics will have to take into consideration the Airstream crossing management.

2.3.1.3.1 Lane characteristics

As mentioned, the traffic using a lane must be homogeneous, meaning aircraft allocated to the lane have similar flying envelope and capabilities. The speed is the primary criterion for defining a lane. Each lane is defined by an interval of speed known as a Speed Family (SF). The number of families determines the maximum number of horizontal lanes available in an Airstream. To build these families, the speed distribution (number of flights per speed) of the traffic sample is used. The speed distributions of the chosen days of traffic are very similar, showing a greater density in the speed range 330 – 510 NM (as shown in Figure 13).

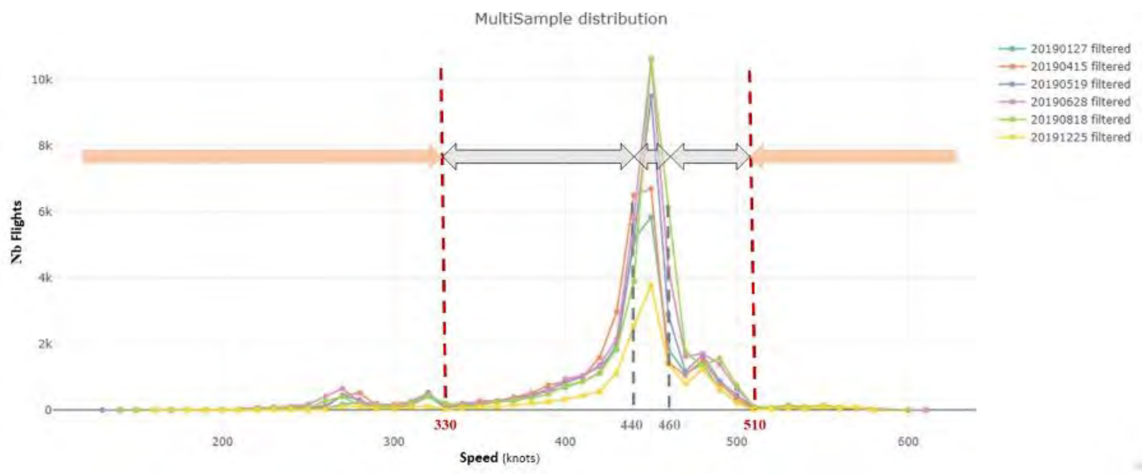


Figure 13 Distribution of speed in the traffic samples

This distribution is used to define the two border-families (i.e. 3 – 330 & 510 – 660). The remaining central part is then equally distributed among the so-called central families whose number is a parameter of the algorithm. Tables below summarizes the results for a test sample with 3 central families defined.
For each family it is necessary to define an available "capacity" to compute the needed number of lanes to build the Airstream. This is performed through the Slot Index.
As mentioned earlier, each aircraft sharing a lane is at the centre of a slot. Consecutive slots define a longitudinal separation (i.e. the distance between the centres of two consecutive slots) as presented in Figure 14.

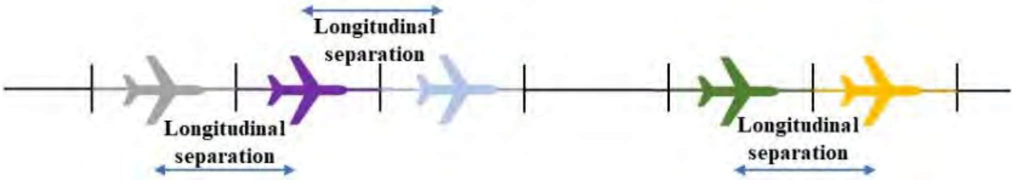


Figure 14. Example of slots distribution on a lane

The Slot Index is defined by equation *Eq. 21* and represents the minimal time between two aircraft for the given family.

$$SlotIndex = \frac{LongitudinalSeparation}{MaxSpeed} \qquad Eq.\ 21$$

Family	MinSpeed	MaxSpeed	SlotIndex
1	0	330	**0,061**
2	330	440	**0,045**
3	440	460	**0,043**
4	460	510	**0,039**
5	510	999	**0,020**

Table 1 Examples of speed families and slot indexes.

These families do characterize the traffic sample. Each individual Airstream has a specific flight pattern due to the aggregated traffic. This pattern is decomposed through three criteria: direction, RFL and SF. Table 2 below provides an example of possible allocation giving the number of flights (Nb Flights) for each pair flight levels (RFL) - S F (Family) of the flights allocated to the Airstream's right side (East-West direction) elements. An indicator is then needed to compare magnitude of the flow and the corresponding family Slot Index. It is the Flow Index, evaluated using formula described by *Eq. 22*.

$$FlowIndex = \frac{24}{Nb\ Flights} \qquad Eq.\ 22$$

It corresponds to the mean time between two flights in a 24 hour time window.

RFL	Family	Nb Flights	FlowIndex
370	2	58	**0,414**
370	3	58	**0,414**
370	4	1	**24,000**
380	2	25	**0,960**
380	3	16	**1,500**
390	2	19	**1,263**
390	3	44	**0,546**
390	4	909	**0,026**
400	2	30	**0,800**
400	3	30	**0,800**
400	4	7	**3,429**

Table 2 Example of RFL – speed family distribution and flow indexes

The ratio of these two indexes (SlotIndex / FlowIndex) gives the occupancy rates of the SFs for each flight level and gives the number of lanes required to serve the associated traffic as explained in Section 2.3.1.3.2.

2.3.1.3.2 Three-dimensional structure of an Airstream

The 3-dimensional structure is closely dependent of the aggregated traffic and can be very different from an Airstream to another. In order to avoid building a labyrinth and allowing Airstreams cross-over, a structure of vertical blocks separated by gaps is proposed. Basic rules are used to move from the specificity of aggregated traffic to the 3-dimensional structure. Various tuneable parameters have been defined for supporting these rules and evaluate the various potential 3-dimensional structures. Seven parameters are defined, as presented in Table 3.

Definition	*Parameter Identifier (unit)*
Floor level of the Airstreams network	MinLevel (FL)
Ceiling level of the Airstreams network	MaxLevel (FL)
Minimal distance between the centers of two consecutive slots	LongitudinalSeparation (NM)
Minimal density of aircraft in lane	MinLevelDensity (%)
Maximum number of lane by side	MaxNbLane
Maximum number of Flight Levels in a vertical block	MaxNbLevelinBlock
Minimal interval between 2 consecutive vertical blocks	MinBTInterval (FL)

Table 3 Parameters for the 3-dimensional structure of Airstreams

Using these parameters, seven rules are applied on the aggregated traffic:

- The traffic outside floor-ceiling levels is removed;
- The lanes below minimal density are removed;
- The calculation of the number of lane(s) per RFL-SF is based on the ratio Slot index over Flow index. If ratio is greater than one, two lanes have to be implemented for the same SF;
- If the number of lanes is greater than the maximum lane threshold, the less populated family is removed until limit is reached;
- The number of lanes evaluation is done independently for the two sides of the Airstream (i.e. asymmetric structure is authorized);

- The number of lanes by side is homogeneous for all the levels/blocks and is set to the maximum number found;
- If a block height (i.e. consecutive levels) is greater than MaxNbLevelinBlock, less populated level is removed until limit is reached;
- If interval between 2 consecutive blocks (i.e. BreakThrough interval) is below the threshold, less populated level from one block (i.e. ceiling or floor level of the 2 blocks) is removed until limit is reached.

Applying these rules leads to the final 3-dimensional structure of the Airstream as the example shown in Figure 15.

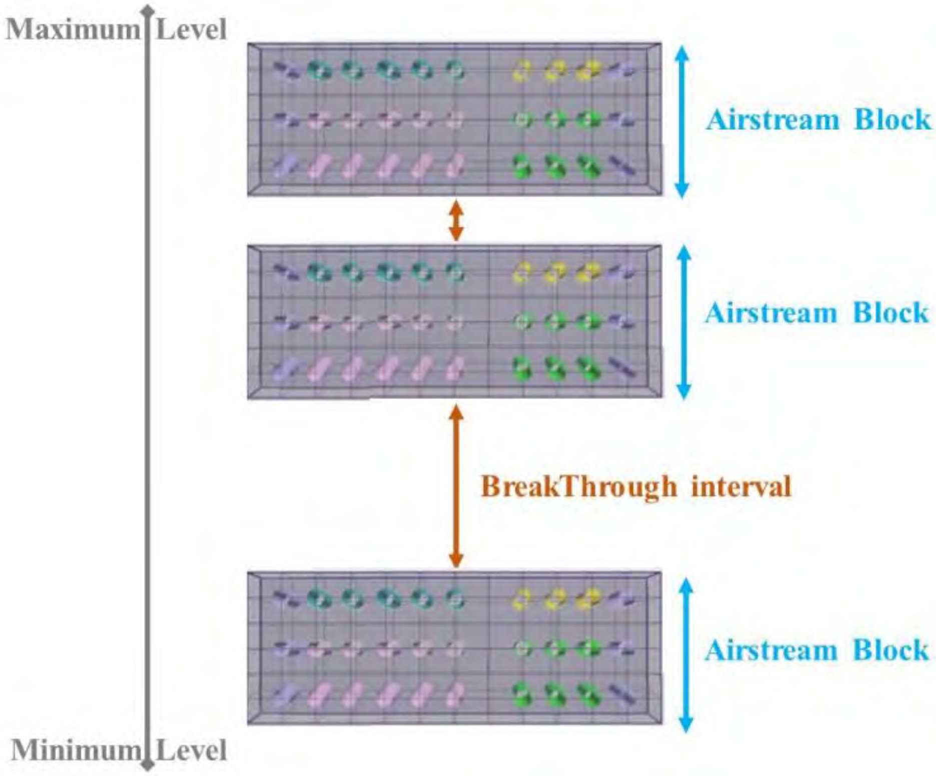


Figure 15 Vertical slice of Airstream tri-dimensional structure

2.3.1.4 Complexity calculation

A lot of work was dedicated to the controller-centric perspective assuming that the complexity is roughly equivalent to cognitive workload. Within this frame, one of the most widely used complexity measures is the dynamic density [15], that combines several operational indicators, such as the number of manoeuvring aircraft, number of level changes, convergence. All these values are used as inputs of a multivariate linear model, or in recent implementations, of a neural network. The tuning of the free parameters of the predictors is made using samples coming from an expertized database of traffic situations. While being quite efficient for assessing complexity values in a given control centre, the method suffers two important drawbacks:

- The tuning procedure requires a large number of expertized samples. A costly experiment involving several air traffic controllers must be set up;
- The indicator is only valid within a specific area of the airspace and has to be tuned when moved to another one. Adapting it to different national airspaces is even more demanding as control practices may diverge.

This approach is not suitable for the evaluation of a new control paradigm or a new airspace configuration since a whole tuning procedure with ATC controller is needed.

The project has explored another way to deal with complexity through purely geometrical indicators [16] [17] that extract salient structural features without referring to the way the traffic is controlled. An obvious benefit is that the same metric may be used everywhere, without the need of a specific tuning. It is also the weak point of the method as the relation with the workload is not obvious.

The approach taken for the complexity assessment is based on a measure of local disorder yielding an indicator pertaining to the last class and uses some of the concepts described by Le Brigant et al. [18]. However, the area studied here is much wider than those described in previous studies. The project has extended this model on the sphere, using stereographic projection.

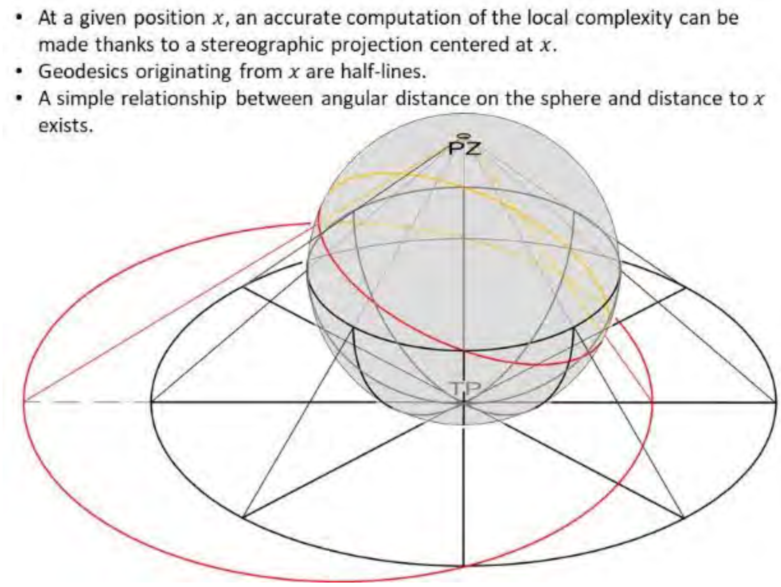


Figure 16 Principle of stereographic projection[3]

2.3.1.4.1 Local linear models in real vector spaces

Local regression is a common statistical smoothing procedure that possesses several interesting features [19]. Let $K: R^n \times R^n \to R^+$ be a kernel function that is most of the time depending only on the distance between its arguments, that is: $K(x, y) = K(\|x - y\|)$, and compactly supported or at least rapidly decreasing.

Starting with a sample set of the form $(x_i, y_i)_{i=1\dots N}$ with $x_i \in R^n, y_i \in R^m$, the local linear model at $x \in R^n$ is the couple $(A_x, v_x), A_x \in M(m,n)$, $v_x \in R^n$ that realizes the minimum of the weighted least square problem:

$$\min_{A \in M(m,n), v \in R^m} \sum_{i=1}^{N} \|A(x_i - x) + v - y_i\|^2 K(x, x_i) \qquad \textit{Eq. 23}$$

Since *K* takes only positive values, the initial problem can be turned into a standard least square one:

$$\min_{A \in M(m,n), v \in R^m} \sum_{i=1}^{N} \left\| A K^{1/2}(x, x_i)(x_i - x) + K^{1/2}(x, x_i)(v - y_i) \right\|^2 \qquad \textit{Eq. 24}$$

[3] Source Wikicommons.

Or in synthetic form:

$$\min_{A\in M(m,n),v\in R^m} tr\left((AX-V)W(AX-V)^t\right) \qquad Eq.\ 25$$

With: $X=(x_i-x)_{i=1\ldots N}\in M(n,N), V=(y_i-v)_{i=1\ldots N}\in M(m,N), W=diag\left(K(x,x_i)\right)\in M(N,N)$.
Taking the derivative with respect to A, v and equating to 0, one obtains the matrix normal equations:

$$\begin{aligned} A_x &= VWX^t(XWX^t)^{-1} \\ v_x &= \frac{(Y-AX)W1}{1^tW1} \end{aligned} \qquad Eq.\ 26$$

With: $Y=(y_i)_{i=1\ldots N}\in M(m,N), 1=\ (1)_{i=1\ldots N}\in M(N,1)$
Please note that the expression for *v* in equation can be written using weighted means as follows. Putting:

$$\bar{X}=\frac{XW1}{1^tW1}, \bar{Y}=\frac{YW1}{1^tW1}, \qquad Eq.\ 27$$

The normal equations become:

$$\begin{aligned} A_x &= \tilde{Y}W\tilde{X}^t\left(\tilde{X}W\tilde{X}^t\right)^{-1} \\ v_x &= \bar{Y}-A\bar{X} \end{aligned} \qquad Eq.\ 28$$

Where: $\tilde{X}=X-\bar{X}, \tilde{Y}=Y-\bar{Y}$.
Since matrix product and inverse depend smoothly on their arguments, clearly the mappings $x\to A_x, x\to v_x$ have the same regularity as the one of the kernel *K*, thus showing the smoothing effect of the procedure. Interpreting the local expression $y\to A_x(y-x)+v\_x$ as a first order approximation to an underlying unknown vector field, v_x is its value at *x* while $A_x$is its derivative. Most of the time, the kernel K is controlled by a positive real parameter *h*, called the bandwidth, and its expression is given by:

$$K_h(x,y)=\frac{1}{h}K\left(\frac{\|x-y\|}{h}\right) \qquad Eq.\ 29$$

While automatic procedures can be used to optimally tune *h*, they rely on an a priori knowledge about the Hessian of the field to be approximated and cannot be used straightforwardly in our problem. Since *h* has the dimension of a length, it represents the characteristic scale of the phenomenon modelled and can be given a realistic value in the order of 100 NM, at least in dense traffic area. For complexity assessment, especially when the flight paths are organized in lanes, it becomes important to capture variations at a larger scale and the effects of the earth curvature cannot be neglected. In fact, an unwanted contribution to complexity will be added due to the intrinsic rotation experienced by the speed vector along the route.

2.3.1.4.2 Local regression on the sphere

Extending the previous approach to a non-Euclidean space is not straightforward as the sampled positions $(x_i)_{i=1\ldots N}$ and speeds $(v_i)_{i=1\ldots N}$ are of different nature. Going back to the original least square problem (*Eq. 23*), several points have to be addressed:

- Definition of a linear vector field on a Riemannian manifold;
- Comparison of tangent vectors in different tangent spaces;
- Definition of a kernel compatible with the manifold structure.

Point 2 can be delt with using parallel translation [15] (Ch. 1). Basic notions about connections are summarized below without proofs.

Let M be a differentiable manifold of dimension *n* with tangent bundle TM. Its space of sections is denoted in the sequel by $\Gamma(TM)$.

Definition 1. A connection on TM is a mapping $\nabla: \Gamma(TM) \times \Gamma(TM) \rightarrow \Gamma(TM)$ *such that:*

$$\nabla_{fX+Y}Z = f\nabla_X Z + \nabla_Y Z, \nabla_X(fY+Z) = X(f)Y + \nabla_X Z, f \in C^{\infty}(M,R), X,Y,Z \in \Gamma(TM) \quad Eq.\ 30$$

A connection on a manifold is a mean to take the derivative of a vector field in the direction of another while ensuring that the result is still in $\Gamma(TM)$.

The action of a connection can be described in coordinates using the so-called Christoffel symbols Γ_{ij}^k. If ∂_i is the i-th canonical section, then, assuming the summing convention on repeated indices:

$$\nabla_X Y = \left(X^i \frac{\partial Y^k}{\partial x_i} + \Gamma_{ij}^k X^i Y^i\right)\partial_k, X = X^i \partial_i, Y = Y^i \partial_i \quad Eq.\ 31$$

The symbols Γ_{ij}^k account for the reference frame infinitesimal variation while the first term is related to intrinsic coefficients derivatives.

Definition 2. A connection ∇ *is said to be without torsion if* $\nabla_X Y - \nabla_Y X = [X,Y], X,Y \in \Gamma(TM)$. *This is equivalent to the Christoffel symbols being symmetric i.e.,* $\Gamma_{ij}^k = \Gamma_{ji}^k$.

Definition 3. Let (M,g) *be a Riemannian manifold. A connection* ∇ *on TM is said to be metric if for any vector fields* X,Y,Z *in* $\Gamma(TM)$*:*

$$X\big(g(Y,Z)\big) = g(\nabla_X Y, Z) + g(Y, \nabla_X Z) \quad Eq.\ 32$$

The next proposition is particularly important in Riemannian geometry and can be proved using the Koszul formula [16](p. 25).

Proposition 1. On any Riemannian manifold, it exists a unique metric connection without torsion, called the Levi-Civita connection and denoted by ∇^{lc}.

Proposition 2. Let M be a differentiable manifold and ∇ *a connection on TM. Let* $\gamma : [0,1] \rightarrow M$ *be a smooth path with* $\gamma(0) = p, \gamma(1) = q$. *For any tangent vector* $v \in T_pM$*, it exists a unique curve* $\tilde{\gamma}: [0,1] \rightarrow TM$ *such that:*

$$\tilde{\gamma}(0) = v, \pi \circ \tilde{\gamma} = \gamma, \nabla_{\dot{\gamma}(t)} \tilde{\gamma}(t) = 0 \quad Eq.\ 33$$

The tangent vector $\tilde{\gamma}(1)$ is called the parallel translation of *v* at *q*.

Definition 4. A C^1 *curve* $\gamma : [0,1] \rightarrow M$ *is said to be a geodesic for a connection* ∇ *if:*

$$\forall t \in]0,1[, \nabla_{\dot{\gamma}(t)} \dot{\gamma}(t) = 0 \quad Eq.\ 34$$

Shortest paths between pairs of points are geodesics for the connection is ∇^{lc}. In general, not all pairs of points on a manifold can be connected by a geodesic and if possible, it may not be unique. On the two-dimensional sphere the first property is true, and the second property holds for shortest paths unless points are antipodal. In a neighbourhood of a point however, the Cauchy-Lipschitz theorem allows to define geodesics given an initial tangent vector.

Proposition 3. Let M be a differentiable manifold and ∇ *a connection on TM. Let* $p \in M$. *It exists a starlike open set* $T_pU \subset T_pM$ *and a diffeomorphism* $exp_p : T_pU \rightarrow M$ *such for any* $v \in T_pU$, $exp\ v = \gamma(1)$ *with* $\gamma : [0,1] \rightarrow M$ *the unique geodesic with* $\gamma(0) = p, \gamma'(0) = v$.

T_pM being a vector space isomorphic to R^n, it is possible to fix a basis $e_i, i = 1 \dots n$.

Definition 5 Under the assumptions of Proposition 3, the normal coordinates at p are the real valued functions $x_i : exp_p\, T_pU \rightarrow R$, $i = 1 \dots n$ *defined by:*

$$x_i\big(exp_p \textstyle\sum_{j=1}^n t_j e_j\big) = t_i \quad Eq.\ 35$$

In the Riemannian setting, if the basis $e_i, i = 1 \dots n$ is orthonormal with respect to the Riemannian metric and the connection is ∇^{lc}, normal coordinates are close to Euclidean ones, as indicated in the next proposition.

Proposition 4. Let (M, g) be a Riemannian manifold. Fix a point p on M. For $v \in T_pU$:

$$g_{jk}(exp\ v) \ = \ \delta_{jk} - \frac{1}{3}\ g\big(R\big(v, e_j\big)v, e_k\big) \ + \ O(\|v\|^3) \qquad \text{Eq. 36}$$

Where *R* is the Riemann curvature tensor.

This shows that in normal coordinates at *p*, the metric is tangent to the Euclidean one at order 2.

Normal coordinates can be used to answer point 1 in the list, through the use of a Taylor expansion.

Proposition 5. Let X be a smooth vector field. The Taylor expansion in direction v up to order 2 of X at p is given by:

$$X\big(exp_p\ tv\big) = \tau_p^{exp_p\ tv}\left(X(p) + t\nabla_v X(0) + \frac{t^2}{2}\nabla_v^2 X(0)\right) + o(t^2) \qquad \text{Eq. 37}$$

Where the parallel translation is taken along geodesics.

The proof is quite direct and is a matter of applying the usual Taylor expansion to the field $\tau^p_{\exp_p tv} X(\text{exp\_p}\ tv)$ that lives in $T_pM$regardless of the value of *t*.

The above proposition shows that from an approximation point of view, the equivalent to a linear vector field in a vector space is a linear vector field in Riemannian normal coordinates and yields the required extension to local linear models. Finally, point 3 can be addressed by imposing a constant integral for the kernel, which is the usual requirement in non-parametric statistics.

Definition 6. Let (M, g) be a Riemannian manifold. The Riemannian mesure $\mu_g$is defined on open sets as:

$$\mu_g(U) = \int_U det\ g^t(x) g(x) dx \qquad \text{Eq. 38}$$

Where x stands for local coordinates (one can check through partitions of unity that the definition is still valid if *U* spans several charts domains).

Definition 7 Under the assumptions and notation of Definition 6, let p be a point in M and Ka kernel function defined on R^n. The kernel function K_q is defined for any point q in the image of exp_p by:

$$K_q(x) = K\big(exp_p^{-1}\ x\big)\frac{\big|det\ D\ exp\big(exp_p^{-1}\ q\big)(x)\big|}{d\mu_g(x)} \qquad \text{Eq. 39}$$

Please note that the factor occurring after the kernel *K* is the one defined in [17](p. 209).

Gathering things together, local linear smoothers can be defined on a Riemannian manifold provided the exponential map has a large enough domain as follows:

- Given a dataset $(p_i, v_i), i = 1 \dots n$, in TM and a fixed-point p in M, use parallel translations $\tau^p_{p_i}$ along geodesics to pull back all tangent vectors at the p_i to T_pM.
- Express the points $p_i, i = 1 \dots n$ in normal coordinates at p as $x_i, i = 1 \dots n$.
- Solve a vector linear model with data $\big(x_i, \tau^p_{p_i} v_i\big), i = 1 \dots n$ and kernel $K(x_i, x) = K_{p_i}(x)$.

In the case of the sphere, the above model simplifies greatly as parallel translations along geodesics are just rotations and can be computed using elementary linear algebra.

2.3.2 Stakeholder survey

Two workshops (half a day each) have been held for both sharing the approach and views of the project team but also get feedback and advice from the community. In parallel two informal meetings

with EUROCONTROL Experimental Centre (network team) were organised during the project. Due to the pandemic, all these meetings run virtual.
The workshops were organised around two themes, the first centred on operational aspect and the second more focused on the technical industrial aspect.

2.3.2.1 Operational workshop

This first workshop is dedicated to the operational environment and needs that can be applied to the Airstream concept. It aims also at getting some elements linked to research questions ***Q. 1*** to ***Q. 4***. After presenting the conceptual approach and the work done so far, a brainstorming meeting was organised to capture the feedback of the audience. Prior to this, a polls session allowed to collect the opinions of experts and stakeholders.
The five polls proposed targeted the thematic of the global shape of an Airstream:

- What are the minimal and maximal altitude to define the Airstream Network;
- What should be the ratio of the original traffic captured by the Airstream network;
- How should be defined the lane characteristics/families;
- Is there a target number of families;
- How to define these families.

Details on the proposed answers and the audience responses are available in §8.

2.3.2.2 Industrial workshop

The second workshop focused on the adequation and needed evolutions of the onboard equipment for being able to implement the Airstream concept. The main audience targeted was the aircraft equipment manufacturers and pilots to address research question ***Q. 4***.
The workshop has been structured as the first one, a presentation session for describing the evolution since the previous workshop. Then, a brainstorming session run around the polls introduced at the beginning of the session.
The six polls proposed targeted the thematic of the global shape of an Airstream:

- Is ASRT & Airstream approach possible with current onboard technologies;
- What is missing to allow collaborative management inside Airstream;
- Considering collaborative management inside Airstream what could be the new separation minima;
- Are vertical manoeuvres possible inside Airstream block;
- May Entry/Exit in Airstream be performed differently than described;
- What is the minimal length of an Airstream (NM).

Details on the proposed answers and the audience responses are available in §8.

2.3.3 Simulation facilities

2.3.3.1 ToolKit mock-up

As mentioned in §2.3, one of the elements of the framework is the evaluation-chain based on various software applications. Part of this chain is the toolkit mock-up which allows to generate, customise, and visualise Airstream network. The main components[4] are briefly summarised in Table 4.

[4] The component which is dealing with the cleaning and formatting of the input data (ALL_FT+ files) is not part of the mock-up suite.

Component	Description
Air-Link Generator[5] **(ALG)**	The component implements the Air-Link algorithm. The input data are the Airspace User demand reduced to city pairs information (ADEP, ADES, Aircraft Type, Identifier, Take-off time, Landing time) extracted from initial demand files (e.g. ALL_FT+). It provides a cluster list with identification of their aggregated flights and the list of "orphans" flights. Parameter: threshold of distance variation. **Data flow**: "*Bundling* box".
Airstream Network Builder [6] **(ANB)**	The component provides the tri-dimensional structure of the Airstream network. The input data are the 2D ASRTs and allocated flight lists calculated by the ASG module. **Parameters**: Airstream minimum level, Airstream maximal level, maximum number of levels per block, minimum occupancy factor per lane, lower/higher speed intervals, number of central speed families. **Data flow**: "*Definition of 3D Airstreams Network & Flight Lane allocation* box".
ASRT Generator (ASG)	The component builds the ASRTs. The input data are to the medoids extracted by the BC module. It applies the eligibility parameters of the policy defined for ASRT creation to build the 2D generic ASRTs. **Parameters**: minimum flight level, minimal length. **Data flow**: "*Definition of 2D Airstreams Network & Trajectory aggregation* box".
Display Module (DMC)	This is the global container of the application. It allows the execution of the various dedicated components, as well as the selection/display of the results. **Parameters**: layout parameters. **Data** flow: none.
Demand Parser (DPC)	The component is generating the traffic sample from the initial demand file. The input data are the Airspace User demand stored in various format files (e.g. ALL_FT+, json). Parameters: local storage environment values. **Data** flow: none.
Indicator Library (ILC)	The component implements all the indicators defined (e.g. complexity maps, total flown distance). It can be enhanced with newly defined indicators set. **Parameters**: spherical rectangle definition, complexity filtering level. **Data flow**: the simulation facilities, "*Interpolation* and *Complexity* boxes".

[5] External component of the framework, which is not yet interacting with the ToolKit.
[6] External component which provides data to the ToolKit.

Component	Description
Medoid Clustering Generator (MCG)	The component implements the K-medoids algorithm. The input data are the traffic samples extracted from the traffic demand files (i.e. ALL_FT+). It provides the initial definition of the ASRTs which will build the network. The selected medoids represent real planned trajectories. **Parameters**: total number of clusters, total number of cycles. **Data flow**: "*Bundling* box".
Reallocated Traffic Generator (RTG)	The aim of the component is to calculate the new trajectories for the flights involved in the Airstream network. The input data are the 3D description of the Airstream network generated by ANB and the original traffic. Projection used for the "re-routing" algorithm is oblique Mercator. **Parameters**: climb/descent rate, mean climb/descent time, minimum turning angle, projection type. **Data flow**: "*3D re-routing & Dynamic Traffic Generation* box".

Table 4 Components of the FC2A ToolKit

All the components, except external ones[7], are coded in JAVA.

2.3.3.2 Assumptions

For the evaluation step, it is necessary to define the targeted perimeter and thus the assumptions made. Some of these are the results of the survey (poll questions) performed during the workshops (refer to § 2.3.2). Some other assumptions have been discussed during various presentations and workshops (i.e. no direct question in a poll). They are presented below:

- Airstream section is considered rectangular;
- Traffic in Airstream is bi-directional (i.e. one direction on each side of the ASRT as shown in Figure 17);
- A lane is defined by an interval of cruising speed;
- A longitudinal separation (two aircraft on the same track) of less than 20NM (transatlantic rails);
- A 5NM lateral separation between two lanes;
- A vertical separation between 2 lanes of 1000 feet;
- The lanes will be created to serve the traffic but without exceeding 5 lanes per side;
- Access to/from Airstream is the direct path (i.e. no use of SID & STAR);
- Climbing/descending phase are made at constant rate (set to 5%);
- Minimal level for the Airstream network is FL320;
- Maximal level[8] for the Airstream network is FL660;
- In the Airstream, the flight has a constant speed on its lane;
- Number of SF is set to 5;
- Target for the traffic managed by the Airstream network is 60% to 80%.

[7] Airstream Network builder is a R script, while Air-Link Generator is a Python software.
[8] The value differs from the results of the workshop. For more details refer to § 2.3.2.

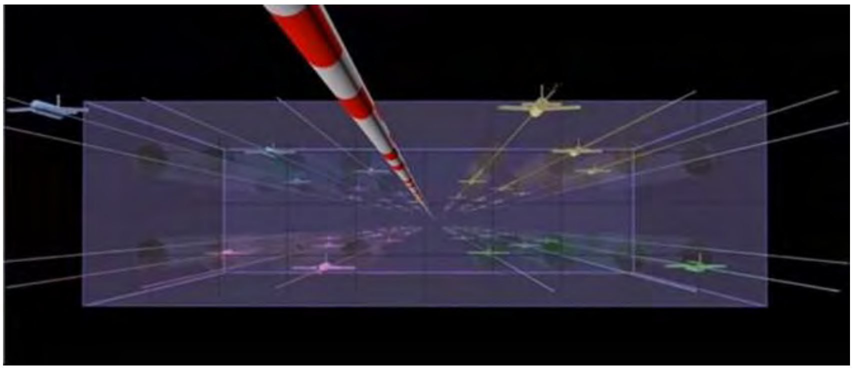


Figure 17 Vertical section of an Airstream structure

2.3.3.3 Medoid clustering

To identify the most relevant values for the configuration parameters and consider the probabilistic aspect of the algorithm several "tuning campaigns" are performed. The first objective is to obtain the best aggregation ratio, i.e. the percentage of flights of the eligible traffic allocated to ASRTs.
The initial parameters studied were those directly linked to the algorithm itself:

- Number of medoids to be generated;
- Number of computing cycles,
- Computation time.

Multiple runs using the test sample over various configurations for the parameters have been performed and summarised in the table below.

Nb medoids	Nb cycles	Mean Execution Time (minutes - seconds)	Mean captured traffic (%)	Mean valid ASRTs (%)
10	10	3 - 50	46%	65%
10	15	5 - 35	56%	80%
10	30	10 - 50	51%	70%
20	10	7 - 30	62%	78%
20	15	11 - 10	***66%***	***83%***
20	30	21 - 00	63%	78%
25	10	9 - 15	58%	78%
25	15	13 - 35	***69%***	***88%***
25	30	26 - 30	58%	78%

Table 5 Tests for various configuration parameters

When the number of ASRT increases, other parameters have to be considered for building the tri-dimensional structure of the Airstream network. It is about the network overall efficiency and the number of "hotspot crossing". A hotspot crossing is a complex crossing situation which involves more than 2 ASRTs in a small vicinity. The parameters are:

- Total number of ASRTs crossings;
- Total number of hotspot crossing.

Multiple runs show that regarding "internal complexity" factor, there is no systematic link with the other parameters. It means that for each run of the ASRT generation, they have to be visually evaluated.
Anyway, the probability to have complex crossing increases with the number of ASRTs. Two examples are presented below.

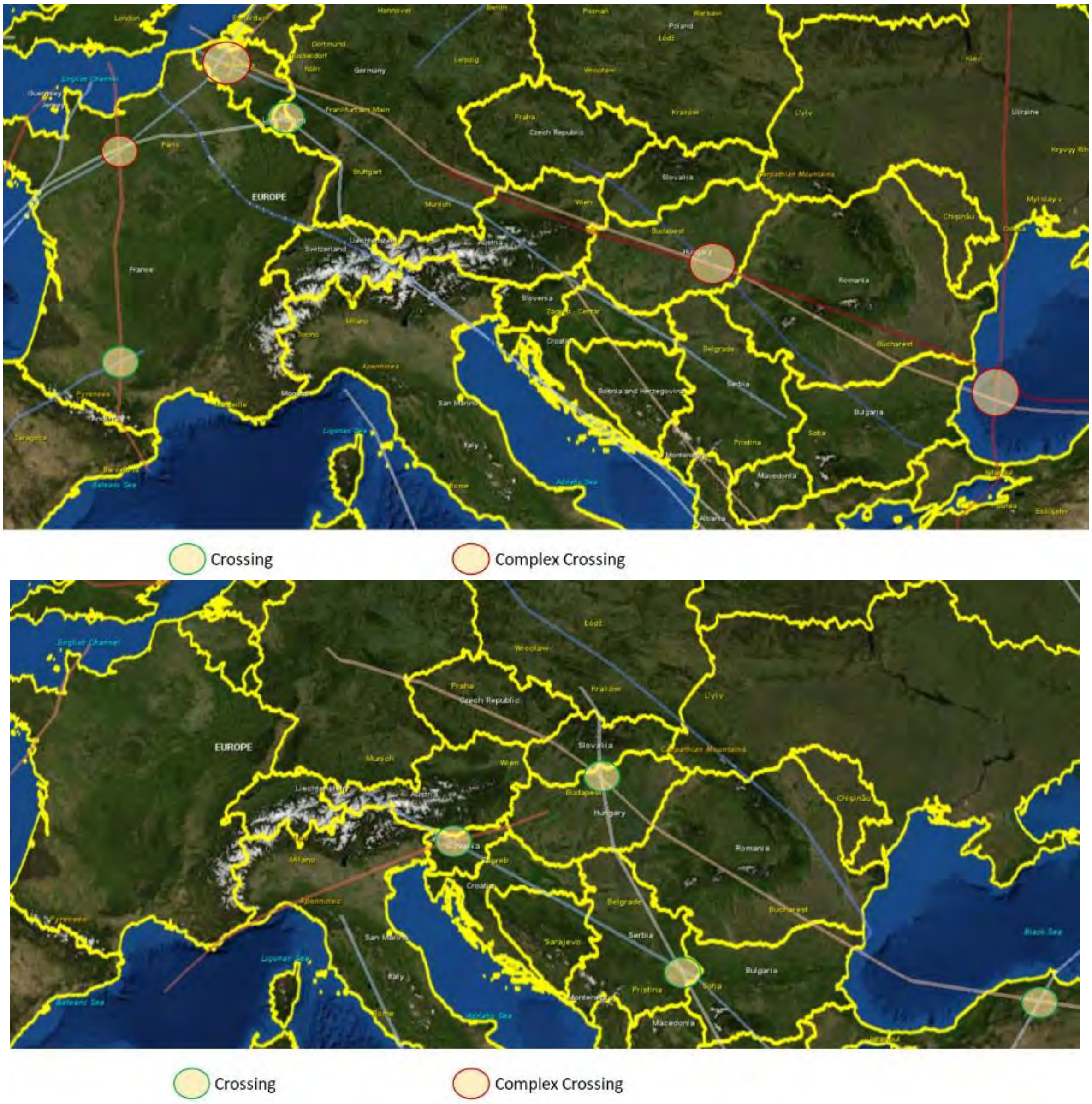


Figure 18 Example of crossing occurrence for test sample (25-15 top) (20-15 bottom)

Considering results reported in Table 5, the configuration "20-15" is chosen as it provides acceptable results on eligible traffic capture and should limit the occurrence of hot spot crossing.

2.3.3.4 Air-Link clustering

For the Air-Link clustering algorithm, two parameters (refer to §2.3.1.2) are evaluated for tuning it:

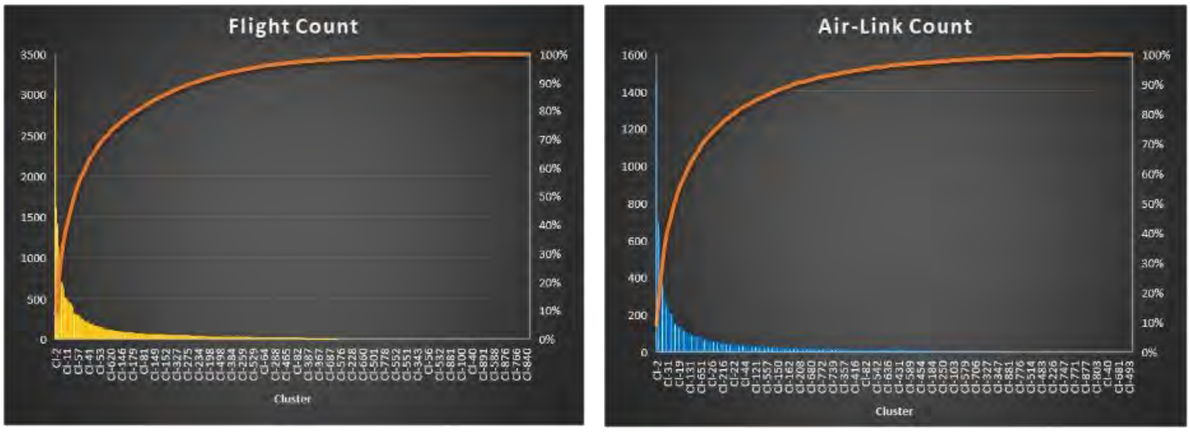
- Maximum deviation angle;
- Maximum distance extension.

The algorithm is composed of two phases:

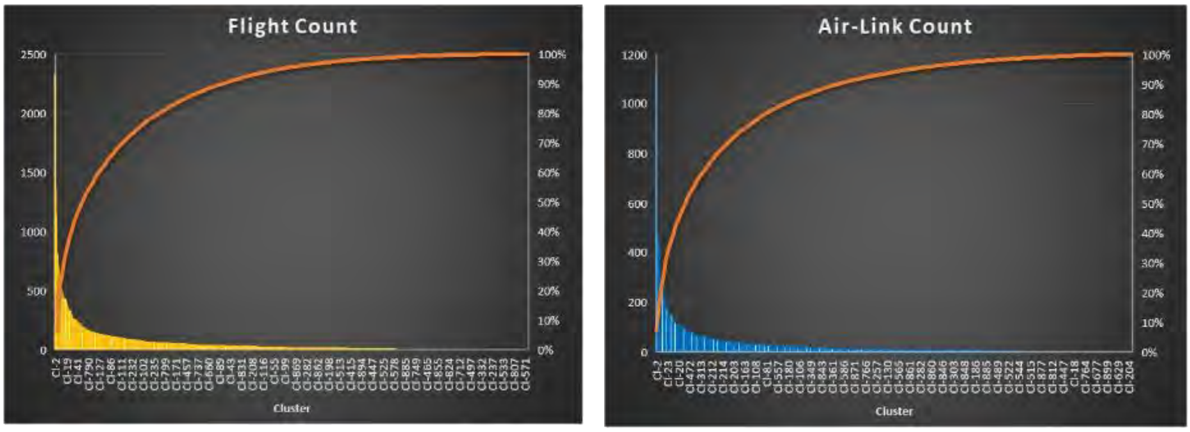
- Phase 1 => choice of the Air-Link with the longest distance to compose the initial cluster and search for other Air-Links for which the two criteria above should be evaluated:
- Phase 2 => eliminate all Air-Links associated with each cluster and try to allocate the Air-Links again using the two criteria, but possibly using a more restrictive value for the distance extension.

Various couple of these parameters have been applied on a test sample, and some results are presented here. The deviation angle is set to 5 degrees. The indicated values represent the maximum distance extension allowed for each step of the calculation. For instance, notation "*0.3 – none*" means: Maximum extension for phase 1 is 30% and phase 2 not activated.

0.3 – 0.3



0.3 – 0.15



0.3 - None

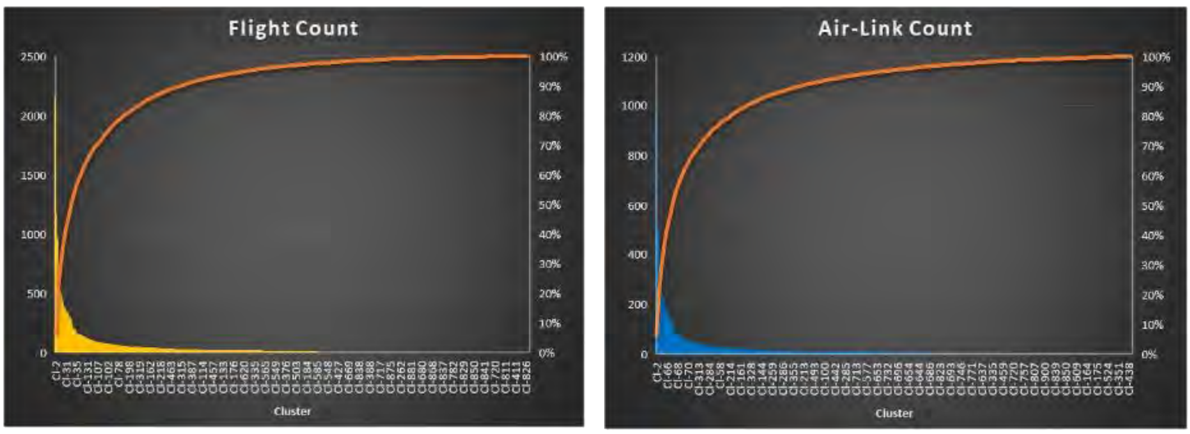


Figure 19 Flight counts and Air-Link counts distribution for various setting of the parameters

These results are summarised in Table 6.

	0.3 – 0.3	0.3 – 0.15	0.3 - None
Traffic aggregated by clusters*	96.6%	93.2%	94.5%
Total number of Clusters*	264 (3048)**	346 (2319)**	350 (2144)**
Total number of orphan flights	1121	2236	1801

* A cluster should aggregate at least 10 AirLinks

** Maximum number of flights aggregated by one cluster

Table 6 Main results of Air-Link clustering depending on the setting of parameters

Even though the percentage of aggregated traffic is the lowest while orphan flights have the greatest value, it has been decided to choose the “30% - 15%” parameters configuration (angle is set to 5°) to be applied on the selected traffic samples.

2.3.3.5 Airstream structure

As already mentioned, the speed distribution of the various samples is very similar. The same behaviour is also found when looking at the distribution per flight levels. Figure 20 presents the repartition of the families (as described in Figure 13) per RFL. The speed of the X axis is the mean speed of the family.

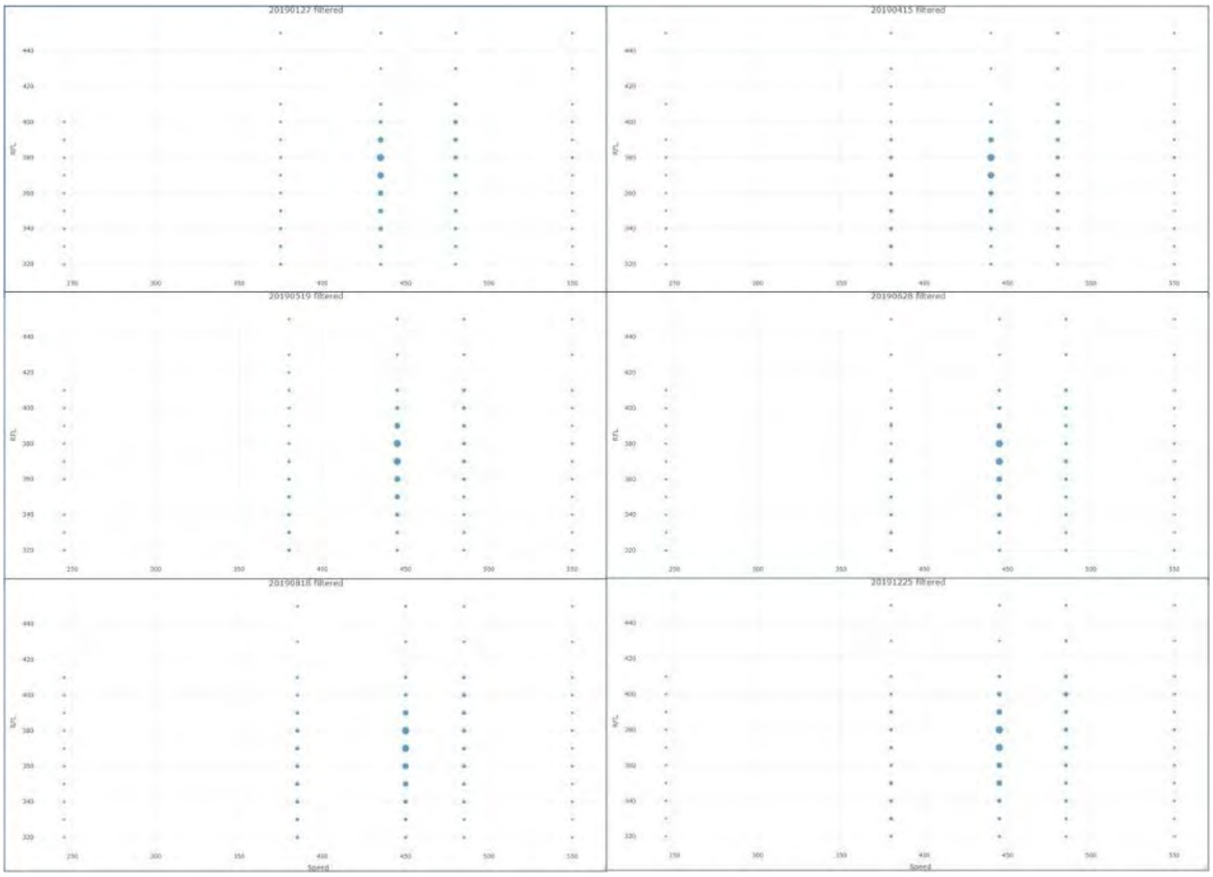


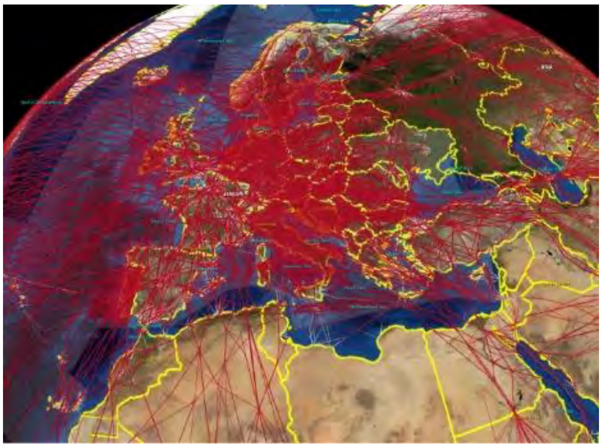
Figure 20 Distributions of SF versus RFL for the six samples

Even though there are some small variations in the definition of the families speed intervals, the general shape is the same for all the studied samples. it shows a concentration of flights in the speed range around 450 knots for altitudes between FL360 and FL390. So, it looks that whatever the traffic type is (i.e. Low, Medium or High) or the type of day (i.e. weekday or week-end), the distribution is

quite reproducible from one day to the other. This needs to be verified by studying a wider range of days. It has been then decided as a first step, to evaluate the family ranges based on the global eligible traffic, instead of evaluating those on the ASRT's individual aggregated traffic.
Regarding the Airstream tri-dimensional structure, the main constraint is linked to the vertical dimension and the need to keep breakthrough intervals as mentioned in §2.3.1.3. The study considers 13 levels in an Airstream structure. It therefore seems logical to consider that a minimum of 3 breakthrough intervals must be targeted. Thus, the potential values for the maximum number of consecutive levels in a block can be 3, 4 or 5.
However, it supposes a homogeneous distribution of the traffic along the various levels. Considering the various samples, default value for the vertical threshold per block is set to 4 assuming no hotspot crossing is authorised.

2.4 Results

Runs of the Air-Link approach have been performed outside the mock-up infra-structure, results are described below in §2.4.1.
Once the technical parameters of the mock-up are agreed, the same storyboard is applied for the selected traffic samples.

Step	Action	Result
1	Extract data from the ALL_FT+ file & generate the FC2A traffic sample	
2	Generate the ASRTs	

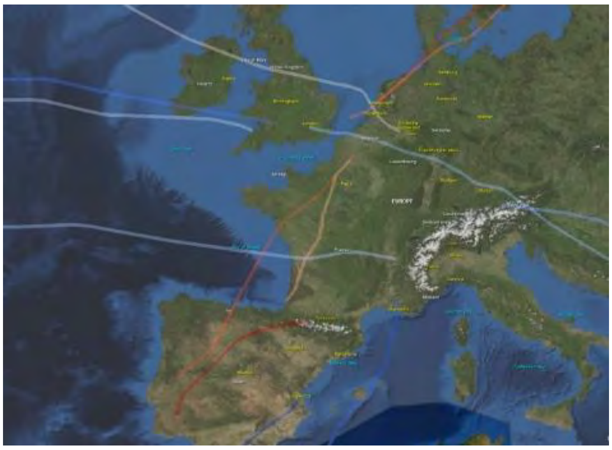
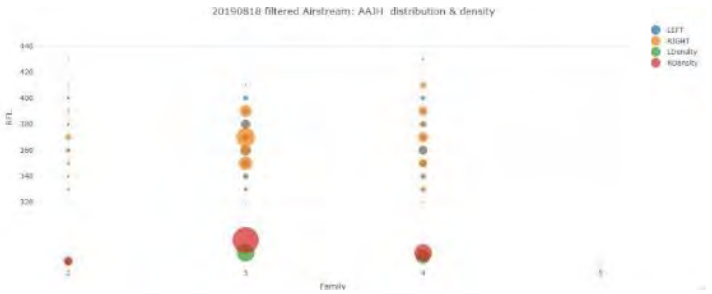
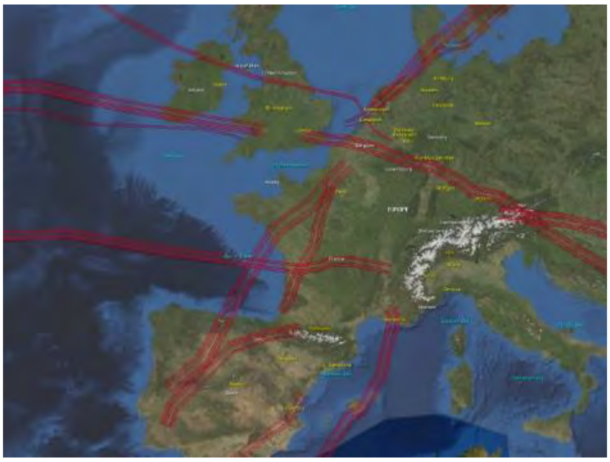
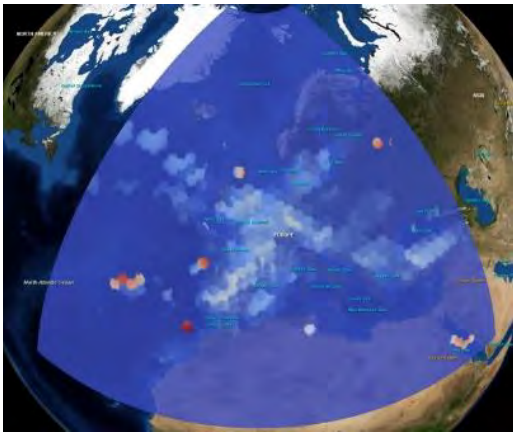
Step	Action	Result
3	Evaluate the ASRTs backbone	
4	Generate the Airstream network (tri-dimensional structure)	
5	Generate the Airstream network traffic	
6	Calculate indicators	

Table 7 Main steps of the FC2A ToolKit mock-up

The results for each of the samples are presented in §2.4.2.

2.4.1 Air-Link approach

The approach has been performed on low (Sample I) and peak (Sample IV) traffic samples. The results are summarised below.

The distributions of flights counts, and Air-Link counts in the clusters are presented in Figure 21. It represents result for a "0.3 – 0.15" configuration.

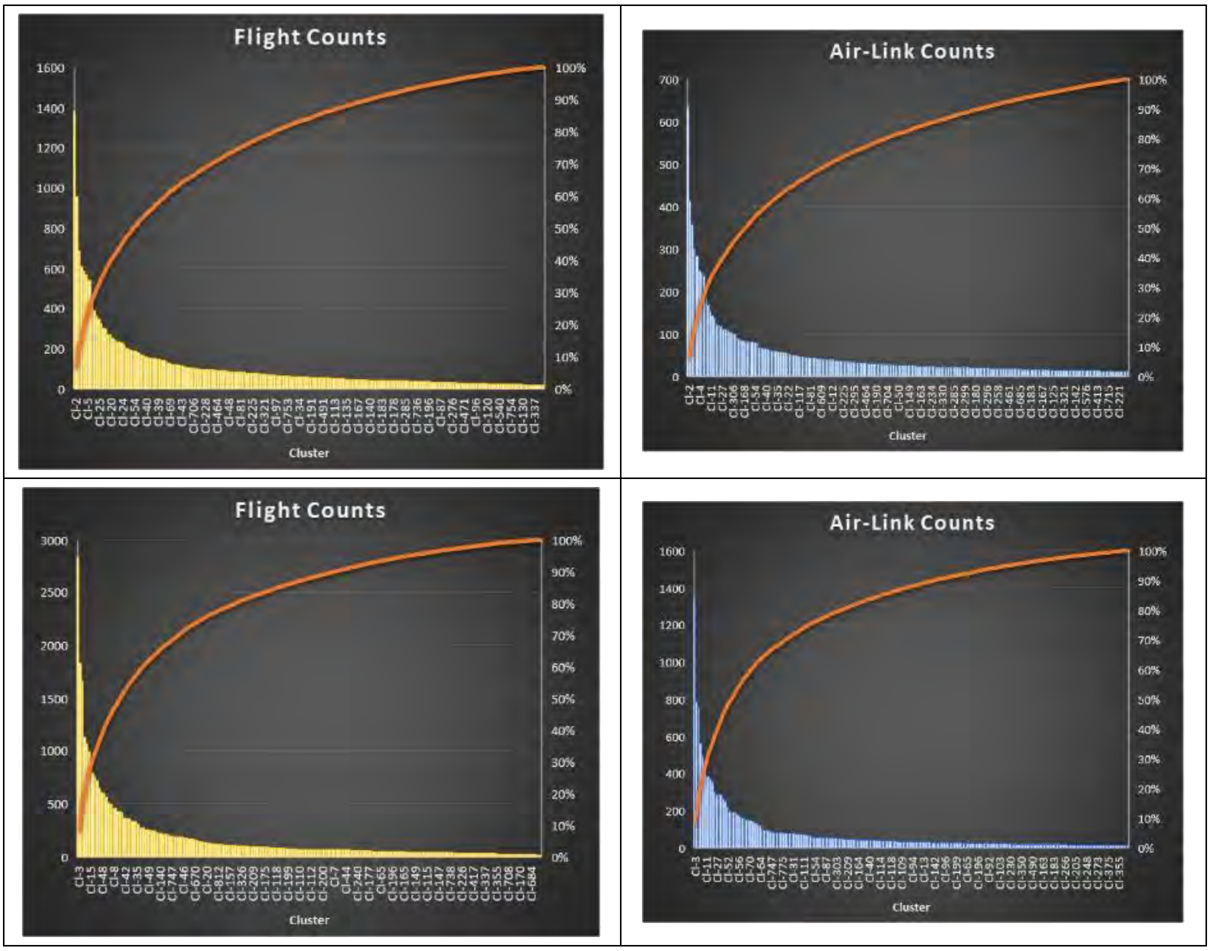


Figure 21 Distribution of flights and Air-Links counts for the clusters in Sample I (top) & Sample IV (bottom)

2.4.2 Airstream network

2.4.2.1 Tri-dimensional structure

At least 4 potential ASRT backbones have been generated for each traffic sample. Based on the evaluation criteria proposed, the potential candidates are rated in order to select the appropriate configuration. The selection process gives the following results.

Date	Traffic Type	Identifier	Nb Crossing	Nb Hotspot Crossing	Aggregated Traffic	Valid ASRTs	Block Vertical Threshold
20190127	Low weekend	*Sample I*	5	1	65%	80%	*3*
20190415	Average weekday	*Sample II*	6	-	53%	90%	4
20190519	Average weekend	*Sample III*	4	1	68%	80%	*3*
20190628	Peak weekday	*Sample IV*	9	-	69%	85%	4
20190818	Peak weekend	*Sample V*	6	-	62%	80%	4
20191225	Low weekday	*Sample VI*	4	-	53%	70%	4

Table 8 Characteristics of the ASRT network selected for each traffic sample

As shown in Table 8, the complete set of criteria is not fulfilled for all samples. For samples I and III none of the produced configurations were without hotspot crossing, whereas for samples II and VI the minimum traffic aggregation ratio is not met. Regarding samples I and III, in order to take into account the hotspot crossing, the vertical threshold is set to 3.

The generation of the tri-dimensional structure for the various samples is presented in the tables below. The tables report for each Airstream the number of flights aggregated by the previous step, the number of flights captured in the tri-dimensional structure (after process described in §2.3.1.3.2) and the ratio of the traffic still managed in the Airstream.

Low traffic samples

Sample I			*Sample VI*		
Aggregated	Captured	Ratio (%)	Aggregated	Captured	Ratio (%)
243	206	85	557	445	80
726	572	79	207	175	85
916	554	60	472	342	72
348	281	81	402	322	80
767	607	79	725	502	69
713	478	67	762	622	82
286	272	95	206	195	95
946	593	63	138	121	88
913	623	68	108	83	77
376	211	56	514	406	79
694	540	78	147	126	86
1223	594	49	207	184	89
887	679	77	389	304	78
537	365	68	797	539	68
322	283	88			
1191	678	57			
11088	7536	72(*)	**5631**	4366	80(*)

(*) Mean value

Table 9 Traffic captured by each Airstream tri-dimensional structure for low traffic samples

Average traffic samples

Sample II			Sample III		
Aggregated	Captured	Ratio (%)	Aggregated	Captured	Ratio (%)
150	130	87	Thickness	InAirstream	Captured
619	450	73	1502	979	65
806	603	75	378	227	60
292	209	72	359	288	80
1392	996	72	653	356	55
342	274	80	958	489	51
114	90	79	694	457	66
54	43	80	1510	979	65
211	182	86	56	46	82
251	181	72	444	365	82
1035	864	83	1504	874	58
1239	696	56	1316	910	69
535	432	81	704	601	85
454	238	52	1088	635	58
859	656	76	1285	716	56
898	635	71	971	720	74
721	538	75	981	556	57
207	173	84			
10179	7390	75	**14403**	9198	66

(*) Mean value

Table 10 Traffic captured by each Airstream tri-dimensional structure for average traffic samples

Peak traffic samples

Sample IV			Sample V		
Aggregated	Captured	Ratio (%)	Aggregated	Captured	Ratio (%)
831	576	69	474	338	71
1135	734	65	450	293	65
1168	767	66	877	630	72
767	630	82	812	522	64
362	285	79	1241	850	68
838	642	77	838	644	77
647	390	60	592	404	68
1792	1050	59	224	167	75
49	37	76	1678	1253	75
2252	1414	63	1165	768	66
606	435	72	309	206	67
687	488	71	1605	1296	81
1423	987	69	1019	725	71
1192	921	77	2251	1641	73
953	774	81	718	587	82
361	272	75	787	547	70
1317	835	63			
16380	11237	71	**15040**	10871	71

(*) Mean value

Table 11 Traffic captured by each Airstream tri-dimensional structure for peak traffic samples

For most of the samples, the process for generating the tri-dimensional structure of the Airstreams is removing roughly 27% of the initial traffic.

2.4.2.2 Traffic reallocation

The last step rebuilds the traffic to compute the new trajectories using the Airstream network. The main assumptions are recalled here:

- Trajectories of all flights allocated to the tri-dimensional structure in the previous step are recalculated;
- "Fly-to" and "Fly-from" segments (departure & arrival paths) are considered as the direct path between the airport and the Airstream point;
- Climbing/descending segments consider a constant rate for reaching either the RFL or the destination airport.
- Flight has a constant speed on its lane while being in the Airstream.

During this process, there are still a small number of flights which are not allocated to the final traffic of the Airstreams. These are mainly flights for which the part of Airstream used is too small or reallocation is not effective. Results are presented here.

Sample	Eligible Flights	Reallocated Flights	Ratio (%)
Sample I	17067	7055	**41%**
Sample II	19467	6932	**36%**
Sample III	21267	8646	**41%**
Sample IV	24058	10455	**43%**
Sample V	24461	10000	**41%**
Sample VI	10744	4179	**39%**

Table 12 Ratio of traffic captured by the Airstream network for the traffic samples

Besides complexity indicator described in the next section, basic indicators have been also computed:

- Variation in mean flown distance;
- Variation of arrival time.

The flight trajectory rebuild for Airstream traffic don't allow to consider indicators on an individual basis. The global traffic relevant for Airstream reallocation (i.e. eligible traffic) is used for generating the indicators, this allows some kind of ponderation of the simple model used for trajectory reconstruction.

The result for each sample is summarised in the table below.

Sample	Mean Flown Distance	Mean Arrival Time (mn)
Sample I	11%	-37
Sample II	7%	-25
Sample III	10%	-26
Sample IV	11%	-29
Sample V	16%	-42
Sample VI	7%	-33

Table 13 Variation of indicators between original and Airstream traffic

It can be noticed that the elongation in distance, roughly 10%, is important but still contained. The variation on the arrival time is not representative as such, since the direct path is used for both "fly-to" and "fly-from" Airstream phases. It is roughly 30 minutes, this is still reasonable and should not significantly alter the complexity calculation.

2.4.3 Complexity evaluation

Due to the simple way used for calculating the fly-to-Airstream and fly-from-Airstream paths, a pre-processing of the sample is performed prior to the complexity evaluation. Only the traffic directly involved in the Airstream network is extracted from the complete sample. To remove side effects linked to the evolving phases of the flight (i.e. climb and descent) an altitude filter is finally applied. The complexity maps for all the samples are presented below. It gives for each sample the maps for the original (left side) and Airstream network (right side) traffic.

Low traffic samples

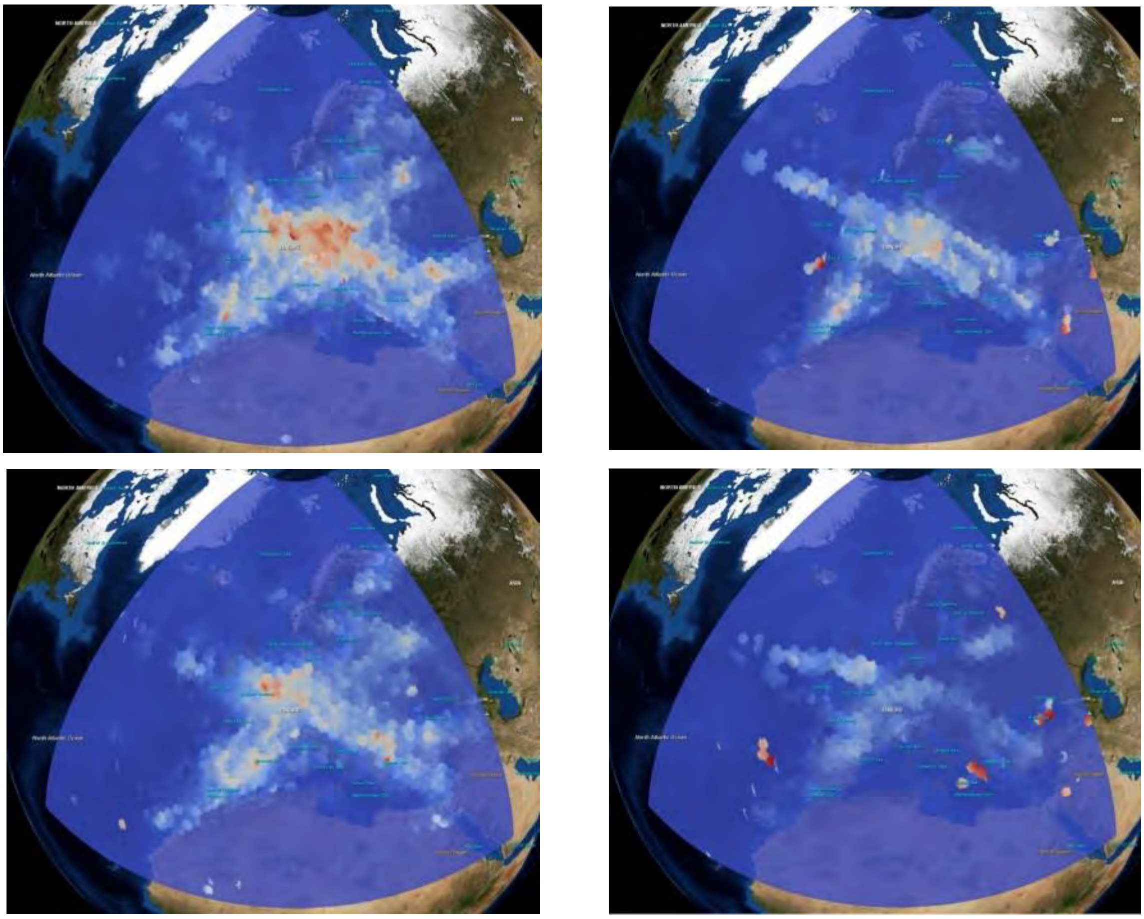
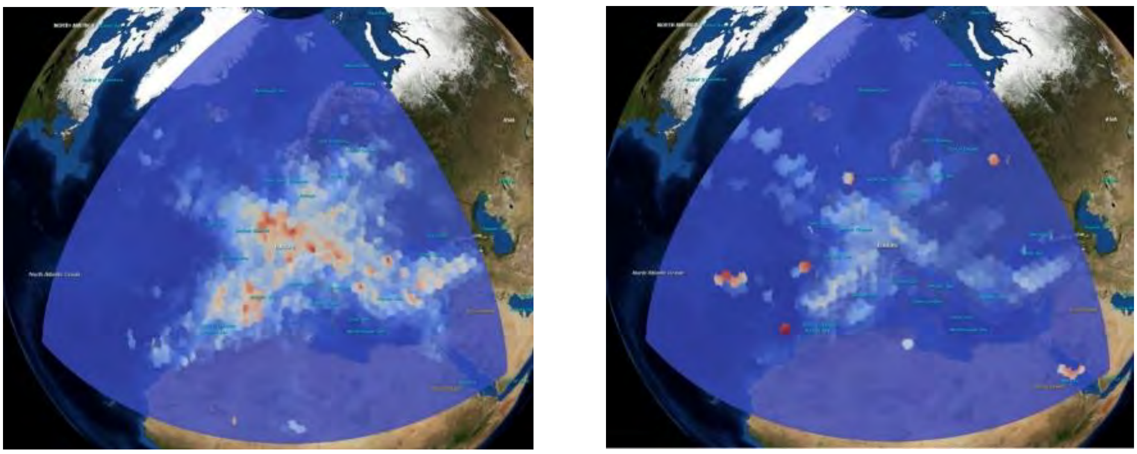


Figure 22 Sample I (top) & Sample VI (bottom) complexity maps

Average traffic samples



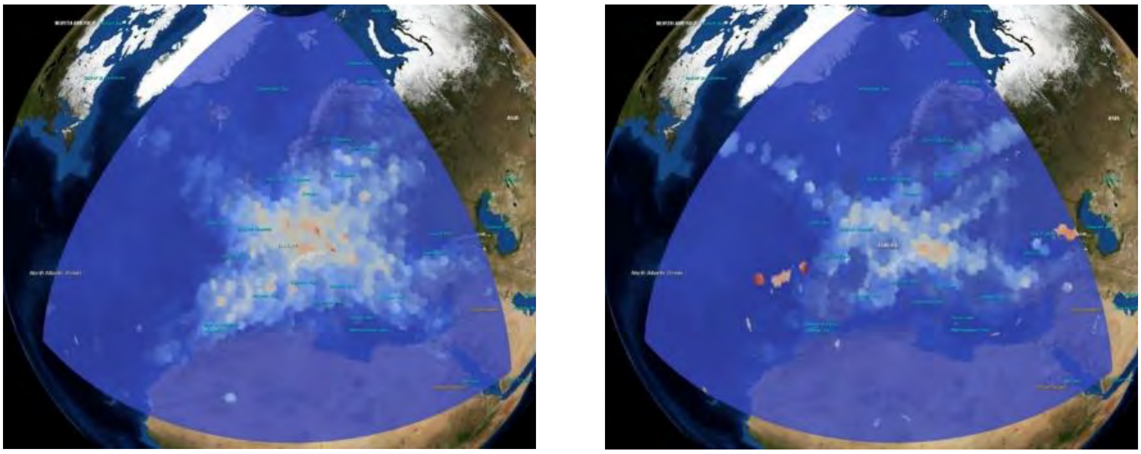


Figure 23 Sample II (top) & Sample III (bottom) complexity maps

Peak traffic samples

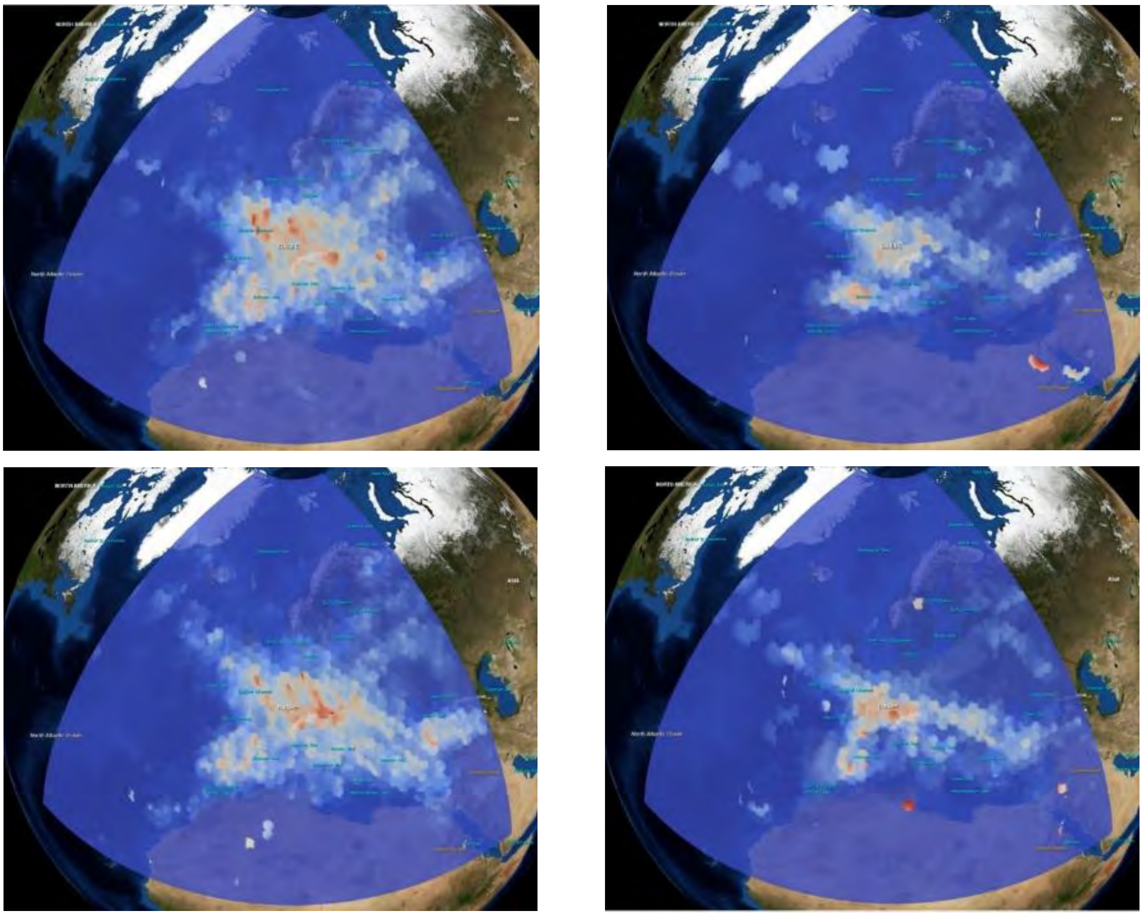


Figure 24 Sample IV (top) & Sample V (bottom) complexity maps

It can be noticed that the Airstream structures are generated less complexity than the original traffic. In order to characterise this drop in complexity, its mean value on the area of interest is computed. It represents the sum of the complexity on the whole map divided by the number of grid cells. It can be seen in the table below which is reporting the mean complexity indicator for all the samples.

	Sample I		Sample II		Sample III		Sample IV		Sample V		Sample VI	
	Original	Airstream	Original	Airstream	Original	Airstream	Original	Airstream	Original	Airstream	Original	Airstream
Mean Complexity	1,746	1,034	1,642	0,886	2,095	1,162	2,367	1,401	2,191	1,294	1,19	0,701
Complexity Decrease	-41%		-46%		-45%		-41%		-41%		-41%	

Table 14 Mean complexity indicator for traffic samples

Globally for all the samples there is a decrease in mean complexity around 42% compared to the initial traffic. Anyway, it should be reminded that these results correspond mainly to the cruise part of the trajectories. Introducing the evolving sections might induce a small change in the evaluation, but without removing the advantage of the Airstream network.

3. Conclusions, next steps and lessons learned

3.1 Conclusions

The FC2A project has contributed to delineate the approach of flow corridors for the management of traffic in highly dense airspace over Europe.

Using new and improved clustering algorithms it has been found that it is possible to define main flows in upper-level coexisting with the classical short haul and regional traffic.

Workshops with both operational and industrial communities have shown a global interest to the concept and initial results presented by the project. The participants of the two workshops have actively discussed and propose refinement of the concept and approach.

Evaluation of indicators has shown that the elongation of distance could be acceptable and that there is a potential reduction (30 to 40%) in the structural complexity of the traffic with the introduction of an Airstream network in the European airspace.

Finally, considering the eligible and reallocated traffic at the end of the process, the initial target for the captured traffic ratio discussed with the experts is not met yet. However, these results are promising, as the actual amount of traffic allocated to the Airstream network represents the lower limit of the concept. The potential improvement of the methodology for defining the tri-dimensional structure of the Airstream and the allocation of traffic should allow to reach the expected ratio of 60 to 70%.

The 2 workshops and working sessions with different operational and industrial actors allowed to get their feedback and to refine the hypotheses and parameters in order to set up a structured approach in the implementation of the concept. This also allowed the development of a first demonstrator (AirStream Factory). Thus, it helps the TRL maturation of a technical solution and to put in place the basis for the initialization of an operational mock-up and reaching a higher TRL level in future activities.

3.2 Next steps

The future activities are structured around two main areas:

- Improve clustering mechanisms:
    - Couple clustering mechanism and complexity calculation in order to introduce a quality indicator for the generated medoids allowing a ranking of the various series provided and enhance the complexity metrics. This approach is currently explored and might ultimately allow the use of deep learning in conjunction with an expertized database to produce a complexity metric with low tuning requirements. As indicated in [18], a by-product is the ability to compute distances between traffic situations, allowing for an efficient indexing in dedicated databases;

- Couple clustering approaches (medoids & Air-Link) in an integrated process by first splitting the overall traffic into sub-samples through the Air-Link approach and then apply the medoid calculation on these sub-sets;
- Improve Airstream network definition and traffic:
  - Improve tri-dimensional Airstream construction methodology, mainly by introducing reallocation mechanism for moving flights adequately from the lanes which are located on a level freed in the process for allowing breakthrough spaces. (e.g. introduce re-affectation of flights);
  - Reshape the initial medoids to trajectories closer to an orthodromic route providing ASRTs closer to a direct route;
  - Initiate the definition of the methodology to be applied for Airstream crossing;
  - Enhance re-routing trajectory algorithm especially the fly-to and fly-from portions of the path (i.e. not use the simplistic direct path) and use a dynamic model (e.g. total energy model based on BADA) for calculating the 4D trajectories;
  - Introduce capacity and slot management within the Airstreams linked to the re-routed 4D trajectories;
  - Evaluate environmental benefits of the Airstream network;
  - Collaboration and/or integration of outcomes of other Engage KTN projects (e.g. DIAPasON).

Complementary activities are also envisaged:

- Generating 2035 traffic samples and evaluation of the contribution of an Airstream network in this context;
- Use data from Research repository;
- Federate in a common suite external tools;
- Improve selection mechanism of the RFL for flights with multiple values field (ALL_FT+);
- Evaluate new calculation method of the distances in medoid approach;
- Evaluate potential evolutions of the structural plasticity/adaptability of the Airstream network regarding disturbances (e.g. meteorological, operational events).

3.3 Lessons learned

A step-by-step treatment is not the best approach. There are interactions between the initial ASRT set and the efficiency of the generated Airstream network especially regarding crossing management. A recursive mechanism based on limited set of relevant metrics might allow to improve the global efficiency of Airstream generation cycle.

The methods applied for computing the route segments accessing and exiting the Airstream network must be carefully studied and evaluated as they may jeopardise the benefits on complexity of the use of main flows by inducing an unmanageable complexity of the evolving airspace volumes.

The time needed for the promotion of an event, especially when a specific Activities dedicated to promoting an event organised by the project and encouraging people to participate, especially if the target audience is related to a particular field, should be started well in advance of the planned date. One and a half months was not completely sufficient for the second workshop dedicated to the industrial aspect.

4. Dissemination

The main dissemination activities are presented below.

Event	Event Type	Organiser	Date	Publication Type[9]
2nd KTN Summer School 2020	Summer School (virtual)	Engage	21st – 25th September 2020	Presentation
SIDs 2020	Conference (virtual)	SESAR JU	07th – 09th December 2020	Poster
3rd TC2 Workshop	Workshop (virtual)	Engage	25th January 2021	Presentation
FC2A Operational Workshop	Workshop (virtual)	FC2A project	15th February 2021	Presentations & Brainstorm session
FC2A Industrial Workshop	Workshop (virtual)	FC2A project	15th April 2021	Presentations & Brainstorm session
9th IC-EpsMsO 2021	Conference	Learning Foundation in Mechatronics	7th – 10th July 2021	Presentations

Table 15 Dissemination activities (participation to public events)

All the materials produced for the above events have been made available, either via the organising entity website or for the project's events via weblinks provide to the registered participants shorter after the event closes.

Besides, on the NMS website a dedicated webpage is available, as well as announcements related to the project activities are published in the newsfeed.

Finally, two project videos, one dedicated to SID and the second for wider advertising purpose have been produced.

5. References

5.1 Project outputs

[FC2A-1] D. Dohy, J-L. Raoul, G. Mykoniatis and F. Mora-Camino, FC2A Final Technical Report (this document), 2021.

[FC2A-2] G. Mykoniatis and D. Dohy, "Air traffic complexity through local covariance in the context of large areas of operations", Proceedings of 9th International Conference on Experiments / Process / System / Modeling / Simulation / Optimization, 9th IC-EpsMsO, Athens, Greece.

[FC2A-3] D. Dohy, J-L. Raoul, G. Mykoniatis and F. Mora-Camino, "Flight Centric Air Traffic Control with Airstreams: a new approach to traffic flow modelling", Proceedings of 9th

[9] Presentations and articles references are available in §5.1.

International Conference on Experiments / Process / System / Modeling / Simulation / Optimization, 9th IC- EpsMsO, Athens, Greece.

[FC2A-4] D. Dohy, “FC2A in a Nutshell”, FC2A Industrial Workshop, 2021.

[FC2A-5] D. Dohy, “Airstream Architecture: evolutions since 1st workshop”, FC2A Industrial Workshop, 2021.

[FC2A-6] F. Mora-Camino, “Collaborative Traffic Management in Airstreams”, FC2A Industrial Workshop, 2021.

[FC2A-7] F. Mora-Camino, “3D + T Guidance in Airstreams”, FC2A Industrial Workshop, 2021.

[FC2A-8] D. Dohy, “Complexity Measures: evolutions since 1st Workshop”, FC2A Industrial Workshop, 2021.

[FC2A-9] D. Dohy, J-L. Raoul, G. Mykoniatis, F. Mora-Camino and G. Baroin, FC2A video teaser, 2021.

[FC2A-10] D. Dohy, “FC2A: presentation”, FC2A Operational Workshop, 2021.

[FC2A-11] D. Dohy, “FC2A: Approach of the Project”, FC2A Operational Workshop, 2021.

[FC2A-12] D. Dohy, “FC2A: Bundling Mechanisms”, FC2A Operational Workshop, 2021.

[FC2A-13] J-L. Raoul, “FC2A: Airstream Architecture”, FC2A Operational Workshop, 2021.

[FC2A-14] D. Dohy, “FC2A: Complexity Measures”, FC2A Operational Workshop, 2021.

[FC2A-15] D. Dohy, G. Mykoniatis, J-L. Raoul and F. Mora-Camino, “Clustering & Complexity measures of European Traffic”, Engage KTN 3rd TC2 Workshop,2021.

[FC2A-16] D. Dohy, G. Mykoniatis, J-L. Raoul and F. Mora-Camino, “Flight Centric ATC with Airstreams (FC2A): initial approach on adaptative airspace & flow monitoring”, poster session, SESAR Innovation Days 2020, 2020.

[FC2A-17] D. Dohy, J-L. Raoul, G. Mykoniatis, F. Mora-Camino and G. Baroin, FC2A SID video presentation, 2020.

[FC2A-18] FC2A project's webpage on NMS website, https://neometsys.fr/fc2a.

[FC2A-19] D. Dohy, G. Mykoniatis, J-L. Raoul and F. Mora-Camino, “FCA with Airstreams: from Bundling to Airstreams”, Engage KTN Summer School, 2020.

Internal documents

[FC2A-20] FC2A IRS document.

[FC2A-21] Input data filtering guide.

[FC2A-22] ASRT & Airstream building principles.

[FC2A-23] Modelling white paper.

5.2 Other

[1] EUROCONTROL, “Forecast Update 2021 - 2024,” 2021.

[2] Air Transport Bureau, ICAO, “Effects of novel coronavirus (COVID-19) on civil aviation: economic impact analysis,” 2021. [Online]. Available: https://www.icao.int/sustainability/Documents/COVID-19/ICAO_Coronavirus_Econ_Impact.pdf.

[3] ACI, “Economic analysis shows COVID-19 is an existancial threat to airport business,” 2020. [Online]. Available: https://aci.aero/news/2020/04/01/economic-analysis-shows-covid-19-is-an-existential-threat-to-airport-business.

[4] ACI, “Summer traffic review shows international market remains virtually non-existene,” 2020. [Online]. Available: https://aci.aero/news/2020/10/30/summer-traffic-review-shows-international-market-remains-virtually-non-existent.

[5] L. Guichard, S. Guibert, D. Dohy, J.-Y. Grau and K. Belachène, “Improving the ATM capacity by functional division of the traffic: the dual airspace,” EUROCONTROL Experimental Centre, Technical Note 2005-23, 2005.

[6] L. Guichard, S. Guibert, D. Dohy and J.-Y. Grau, “ A Human-In-the-Loop experiment to assess the dual airspace concept,” in *2nd International Conference on Research in Air Transportation*, Belgrade, 2006.

[7] H. Hering, “Air traffic freeway system for Europe,” EUROCONTROL Experimental Centre, Technical Note 2005-20, 2005.

[8] R. Irvine and H. Hering, “Systematic air traffic management in a regular lattice,” in *7th ATM Seminar*, Barcelona, 2007.

[9] A. Yousefi, G. Donohue and L. Sherry, “High volume tube shaped sectors (HTS): a network of high capacity ribbons connecting congested city pairs,” in *23rd Digital Avionics Systems Conference, IEEE/AIAA*, Salt Lake City, 2004.

[10] Joint Planning and Development Office, “Concept of Operations for the Next Generation Air Transportation System, Ver. 2.0.,” Washington, 2007.

[11] A. Yousefi, J. Lard and J. Timmerman, “Nextgen flow corridors initial design, procedures, and display functionalities,” in *29th Digital Avionics Systems Conference, IEEE/ AIAA*, Salt Lake City, 2010.

[12] M. Ab Wahid, H. Bouadi, A. Drouin, B. Panomruttanarug and F. Mora-Camino, “Traffic management along airstreams through space metering,” in *3rd CEAS Specialist Conference on Guidance, Navigation & Control*, Toulouse, 2015.

[13] J. Marcelo de Castro Monteiro, J.-P. Daniel and F. Mora-Camino, “A proposal for collaborative navigation in corridors,” in *IEEE Chinese Guidance, Navigation and Control Conference*, Nanjing, 2016.

[14] L. Kaufman and P. Rousseeuw, Clustering by means of medoids, North Holland / Elsevier, 1987, p. 405–416.

[15] I. Chavel, Riemannian geometry: a modern introduction, Cambridge university press, 2006.

[16] P. Petersen, Riemannian geometry, Springer, 2006.

[17] T. Willmore, Riemannian geometry, Oxford university press, 1993.

[18] A. Le Brigant and S. Puechmorel, “Optimal Riemannian quantization with an application to air traffic analysis,” *Journal of multivariate analysis,* vol. 173, pp. 685-703, 2019.

[19] C. Loader, Local regression and likelihood, Springer, 1999.

[20] G. Mykoniatis, F. Nicol and S. Puechmorel, “A New Representation of Air Traffic Data Adapted to Complexity Assessment,” in *ALLDATA 2018, The Fourth International Conference on Big Data, Small Data, Linked Data and Open Data*, Athens, 2018.

6. Annex I: Acronyms

Term	Definition
ACI	Airport Council International
ADEP	Aerodrome of Departure
ADES	Aerodrome of Destination
ADS	Automatic Dependent Surveillance
AFIL	Air-Filed Flight Plan
ALG	Air-Link Generator
ANB	Airstream Network Builder
ANSP	Air Navigation Service Provider
ASG	ASRT Generator
ASRT	AirStream Reference Track
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
CLARA	Clustering LARge Applications
COVID	COronaVIrus Disease
CTFM	Current Tactical Flight Model
DAC	Dynamic Airspace Configuration
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DMC	Display Module Component
DPC	Demand Parser Component
ECAC	European Civil Aviation Conference
ENAC	Ecole Nationale de l'Aviation Civile
ETFMS	Enhanced Tactical Flow Management System
FCA	Flight Centric ATC
FTFM	Flight Tactical Flight Model
HTS	High volume Tube-Shape sector
ICAO	International Civil Aviation Organization
ILC	Indicator Library Component
KPI	Key Performance Indicator
KTN	Knowledge Transfer Network
MCG	Medoid Cluster Generator
NMS	NeoMetSys
RFL	Requested Flight Level
RNP	Required Navigation Performance

Term	Definition
RTFM	Regulated Tactical Flight Model (by ATFM measures)
RTG	Reallocated Traffic Generator
SES	Single European Sky
SESAR	Single European Sky ATM Research (Programme)
SID	Standard Instrument Departure
STAR	Standard Instrument Arrival
TBO	Trajectory-Based Operations
TRL	Technology Readiness Level

7. Annex II: Glossary of terms

Term	Definition
ALL_FT+	File providing the historical traffic in the ECAC region for one day. Among all set of data provided in the file, 3 types of flight plan / trajectory are available: • FTFM => it is the last filed flight plan from the airline. • RTFM => if ATFM regulation measures are applied, it is the last regulated flight plan information. If no regulation applied, it is the FTFM. • CTFM => it is the information captured in ETFMS after the flight has been operated and Correlated Position Report data is received showing which 4D trajectory it actually followed.
Fly-from path	Trajectory path from the last point of the Airstream to the destination airport.
Fly-to path	Trajectory path from the departing airport to the first point in the Airstream.
ZZZZ	When the departure or arrival airport does not have an ICAO code, this code is applied by default.

8. Annex III: Stakeholder's reply to polls

8.1 Operational workshop

The workshop is targeting the operational side of the concept.

The questions proposed during the polls are reported here.

1. Can we define the families from:
    - o The distribution of speeds?
    - o Another criterion?
2. Are lane characteristics:
    - o Globally predefined?
    - o Specific to an Airstream?
3. Is there a target number of families:
    - o Up to 5?
    - o Between 6 and 10?

- o 10 or more?
- o No target number?

4. What should be the ratio of original traffic captured by the Airstream network:
   - o 0 to 20%?
   - o 20 to 40%?
   - o 40 to 60%?
   - o 60 to 80%?
   - o Greater than 80%?
5. What are the minimal & maximal altitudes to define the Airstream network:
   - o Minimal:
     - FL160?
     - FL200?
     - FL240?
     - FL280?
     - FL320?
   - o Maximal:
     - FL340?
     - FL420?
     - No max?

The answers to these polls are summarised in the graphs below.

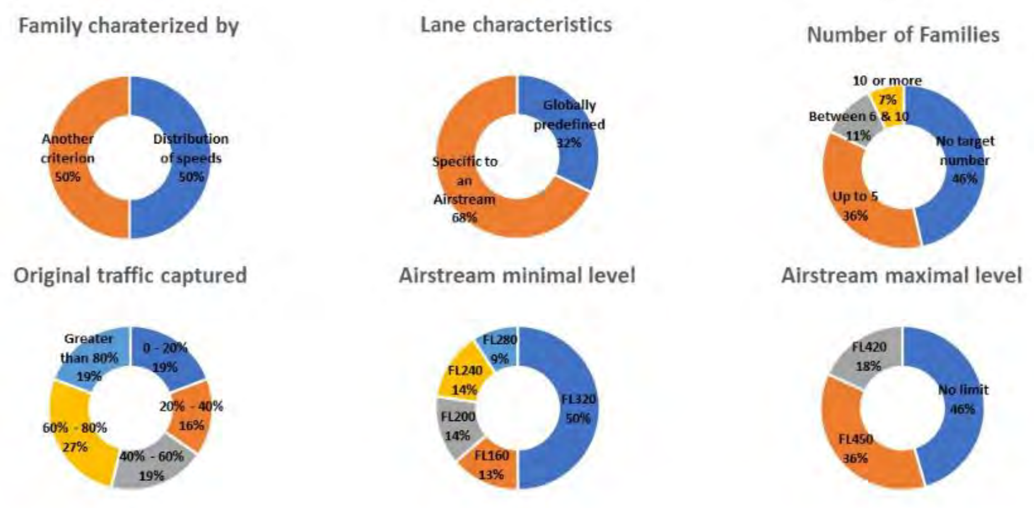


Figure 25 Distribution of votes for Operational workshop questionnaire

8.2 Industrial workshop

The workshop is focusing on the technical side of the onboard equipment needed for fully apply the concept.

The questions proposed during the polls are reported here.

1. Is ASRT & Airstream approach possible with current onboard technologies[10]:
   - o Yes?
   - o No?

[10] Result is not representative as only 18% of the participants have answered to the question.

2. What is missing to allow collaborative management inside Airstream:
    - Navigation equipment?
    - Communication equipment?
    - Surveillance equipment?
    - Procedures?
    - Others?
3. Considering collaborative management inside Airstream what could be the new separation minima:
    - Vertical (ft)
        - 1000?
        - 500?
        - Less?
    - Lateral (NM)
        - 10?
        - 5?
        - Less?
    - Longitudinal (NM)
        - 20?
        - 10?
        - Less?
4. Are vertical manoeuvres possible inside Airstream block:
    - Yes?
    - No?
5. May Entry/Exit in Airstream be performed differently than described:
    - Yes?
    - No?
6. What is the minimal length of an Airstream (NM):
    - 100?
    - 150?
    - 200?
    - More?

The answers to these polls are summarised in the graphs below.

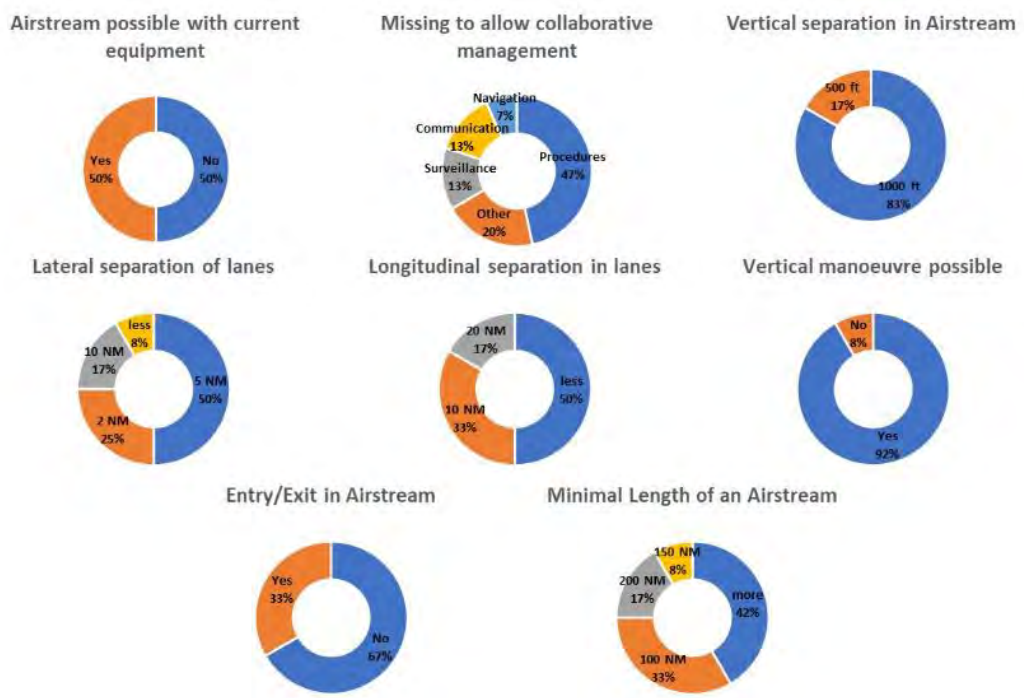


Figure 26 Distribution of votes for Industrial workshop questionnaire

9. Annex IV: Traffic filtering rules

On average, the filtration mechanism on the samples used induces the removal of 8% of the initial traffic.

9.1 Airport management

9.1.1 AFIL and ZZZZ

Flights associated with these airports are excluded from the sample.
They correspond to a flight for which the flight plan was provided after the flight took off (AFIL) or for which the departure or arrival airport does not have an ICAO code (ZZZZ)).
The second case is regularly linked to helicopter flights (e.g. to offshore platforms)

9.1.2 Airports and ECAC area

Flights in the sample can be categorized into 5 classes:

- Domestic =>ADEP and ADES in the ECAC area;
- Incoming => ADEP out of ECAC - ADES in the ECAC area;
- Outgoing => ADEP in the ECAC - ADES area outside the ECAC area;
- Transit => ADEP and ADES outside the ECAC zone[11] but overflying the ECAC area;
- External[12] => ADEP and ADES out of ECAC zone not crossing the ECAC area.

All flights belonging to the first three classes will be kept in the final sample. External flights as well as some Transit Class flights will be removed from the final sample (see 9.3).

[11] It should be noted that some flights (e.g. New York - Johannesburg) have a fairly limited transit time and in a remote area of the central area of the ECAC airspace.
[12] Some EUROCONTROL members are not part of ECAC (Morocco, Israel), flights associated with these countries are present in the ALL_FT files but may not enter the ECAC space (e.g. flight Rabat Abu Dhabi).

9.2 Flight level management

Flight level filtering management uses the required flight level (#82) field of the ALL_FT. When this field has several levels of flight, the highest is taken into account.

Any flight for which the maximum flight level from this field is below the floor threshold level (FL180) is removed from the sample.

9.3 Flight selection

Some flights will not be included in the final sample.

Flights not selected will be those belonging to the External class or Transit for which the flight time in the ECAC zone is "low" and/or the transit space is outside the "central" ECAC area.

The screening mechanism is simple and based on geographical segregation of departure and arrival airports according to quadrans (S_1, S_2, S_3 and S_4) defined in relation to a reference point of the ECAC zone.

Figure 27 Reference point and quadrans in flight selection

The removal rules apply for external flights when:

- ADEP in S_3 and ADES in S_2;
- ADEP in S_2 and ADES in S_3.