SESAR Engage KTN – catalyst fund project final technical report

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1. Abstract and executive summary

1.1 Abstract

A major limitation of the current ATM system is the loss of effectiveness due to the limited integration between the layered planning Decision Support Tools (DSTs). While the Trajectory Based Operation concept enables new DSTs that could deal with present demand/capacity, a word of caution at a practical level: ATM stakeholders realise that technological flexibility to regulate flights into a sector is not synonymous of performance, rather several negative effects can arise at the network level due to lack of analysis of interdependencies among regulated sectors. INTERFACING has developed a formal probabilistic framework to detect and characterise at the network level the flight interactions and their interdependencies. New interaction metrics have been implemented to enable the evaluation of regulation efficiency and to pave the way for the design of mitigation measures for a smooth fine-tuning of traffic demand at a micro level that considers the effects at a macro level improving the network performance.

1.2 Executive summary

Data-driven trajectory prediction methods pave the way not only for a better predictability but also for a true integration at the ATM service system level in which the presently layered ATM planning could exploit the freedom gaps between strategic/pre-tactical (ATFM) and tactical (ATC), to move one step forward to a competitive ATM system in which present ATC resources are used to attend AUs' demands whilst avoiding resource idleness and saturations that foster regulations and/or holdings.

Airspace digitisation opens a window of opportunities to support the modelling of airspace demand **at the micro level by analysing trajectory data** to anticipate the detection of problems/interactions among trajectories that would consume mental effort of ATCs and, in some cases, the implementation of tactical measures. The proper identification of the different interaction zones will facilitate the assessment and exploitation of new ATFCM and STAM mitigation measures in volumes smaller than sectors, providing advantages with respect to conservative measures such as sector capacity regulations, which unfortunately tend to over-constrain the full ATM when more than one regulation is activated.

The granularity of the INTERFACING methodology enables the early detection of precise areas where problems to manage will arise. INTERFACING **proposes a probabilistic framework** to extend the PARTAKE (SESAR ER2 project, GA: No. 699307) data-driven prediction methods for digitisation, trajectory interaction detection and analysis tools and **implements new interaction metrics** to better integrate strategic and tactical information to anticipate ATC problems (i.e. potential co-existence of more than one aircraft in the same airspace volume). These tools are enhanced with a macro level analysis of the interdependencies among interaction zones (distributed through different sectors or spatially concentrated in the same sector) to enable a proper understanding of the spatio-temporal interdependencies among fragmented sector capacity constraints in order avoid the propagation of undesired interaction-zone dynamics through the full ATM system together with the potential upstream and downstream negative effects of capacity regulations.

The project has produced two main outcomes:

- **A formal probabilistic framework for Interaction Zone detection and characterisation**. The following concepts have been formalised in order to assess the airspace state in terms of the Interaction Zones (see Figure 1):

- the **Characterisation** of the possible interaction zones that may appear during the analysed period, considering the uncertainty in the trajectory predictions,
- the **Existence Probability**, which is the probability that these detected interactions zones will finally take place,
- the **Complexity** of each interaction zone, which is a function of its intrinsic properties and,
- the existing **Interdependencies** between the detected interaction zones.

* **A Demonstration suite**. The core of the project developments is a library of functional blocks that works as a pipeline, taking the traffic scenario as the main input, along with the algorithm tuning parameters, and producing the results of the interaction zone analysis. The traffic scenario is described by the set of 4DT trajectories using the so6 file format. The analysis results are represented by a complex data structure (using a new format called VisioJSON, which extends from GeoJSON) containing the detected interaction zones, hotspots, their metrics as well as their interdependencies. Two solutions have been implemented for the visualisation of the INTERFACING analysis results. *AsloEarth* is a visualisation tool created as part of the INTERFACING project to graphically show the objects and metrics produced by the interaction zone analysis. Secondly, a software communication interface for executing the tools from the R-NEST platform, so the ATM community will benefit from the project outcomes through this reference tool.

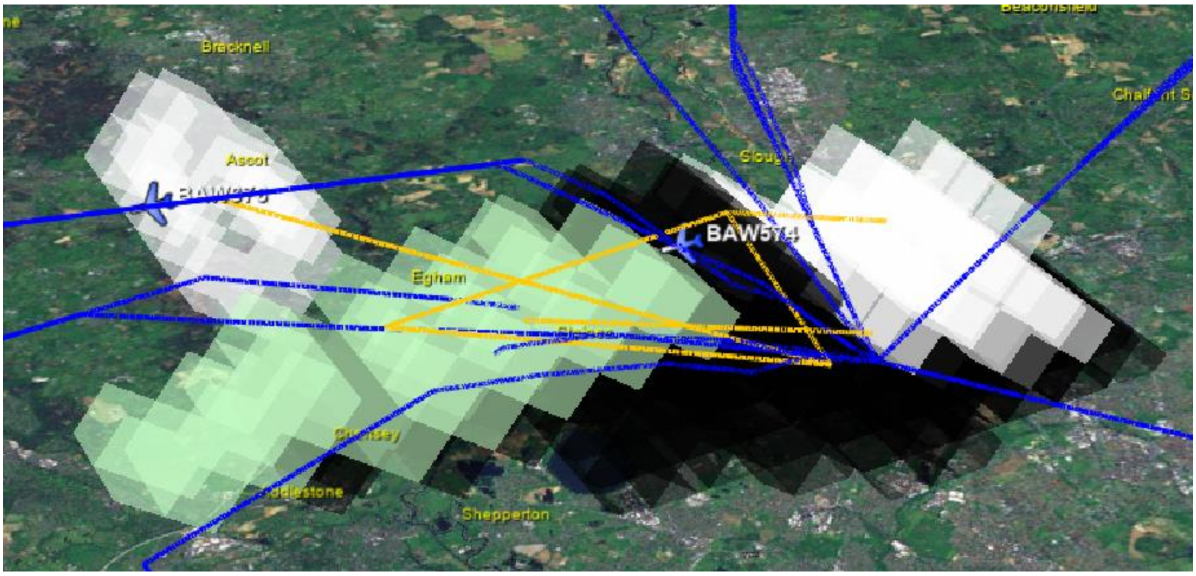

Figure 1. 3D Visualisation of Interaction Zones

On the view of the achieved results, the project has successfully addressed two (expected positive) impacts for ATM:

* **Enhancement of the DCB for the sake of ATC Minimum Intervention**. INTERFACING metrics and the interdependency causal analysis complement and enrich traditional indicators, such as entry and occupancy counts, that participate in the capacity analysis. The Interaction Zones can be framed at sector level, providing a deeper insight on the possible conflicting situation ATC will face. It could be expected that the consolidation of the implemented metrics opens the opportunity to investigate new mitigation measures bridging the gaps between the temporal ATFCM phases, ranging from the LTM to the EAP lookahead with respect to ATC timeframe.
* **Improve transparency and efficiency of DCB network services**. The new metrics and interdependencies provide an insight into the Interaction Zones at trajectory level, so the mitigation measures to remove the interactions can be implemented at trajectory level instead of at sector level. Therefore, an efficiency improvement could be expected since constraints (e.g. a

sector regulation) can be transformed into decision variables (e.g. which is the minimum set of flights that should be regulated to reduce the complexity of a given Interaction Zone or Hotspot). Transparency would benefit from the causal analysis at trajectory level since the need to implement certain mitigation measures can be explained from the up & downstream negative effects a given flight or set of flights are causing.

2. Overview of catalyst project

2.1 Operational/technical context

The INTERFACING project introduces a formal probabilistic framework to identify and characterise flight interactions through the so-called Interaction Zones (IZ): an airspace region in which during a time interval there is a possibility, or not null probability, that two or more A/C will co-exist.

INTERFACING proposes the micro-level analysis of spatio-temporal interactions among trajectories aiming to provide interaction metrics in a time frame ranging from the LTM (6 – 1h) and the INAP/EAP (40 – 10 minutes) lookahead with respect to ATC timeframe. A quick-win of the project has been the implementation of these **new interaction metrics to evaluate the efficiency** of sector regulations **by identifying the demand-capacity imbalances** of sectors in terms of flight interactions causing the emergence of IZ with the otherwise unpredicted dynamics. Furthermore, the **new interaction metric could guide the design of new mitigation measures** for a smooth fine tuning of traffic demand at micro level considering the effects at macro level improving the network capacity performance.

Most likely, the main barriers for the INTERFACING goals could be related to the different sources of uncertainty leading to a lack of trajectory predictability. The proposed methodology has been conceived and developed to overcome those factors that create reluctancy when a method is based on the assumption of trajectory predictability. To remove these potential barriers, INTERFACING has put the focus on the capability to deal with uncertainty and unpredictability in order to produce interaction metrics that can be qualified with a statistical significance. The characteristics of an Interaction Zone, and its existence itself, are formalised by a probabilistic model. The model has a set of parameters that relates both to the geometry and the probability density function (pdf) of a volume where an aircraft is predicted to be present in a given lookahead time. The shorter the prediction lookahead, the denser the pdf, whereas the longer the prediction lookahead, the sparser the pdf.

As a concept, INTERFACING formalises the Interaction Zones and Hotspots, providing a set of new metrics and a causal analysis that opens opportunities for bridging the gaps between the temporal phases of ATFCM, providing a deep understanding and explainability of the upstream and downstream negative effects of mitigation measures, such as regulations applied to the wrong time and sectors. As a project result, a software toolkit has been developed to demonstrate the proposed concept. As an evaluation tool, INTERFACING is suitable for addressing current ATM challenges such as the identification of ‘hotspots’ and the impact assessment of ATFCM and STAM measures.

2.2 Project scope and objectives

INTERFACING project addressed the following key objectives to enrich a smart and efficient coordination of demand management to preserve declared sector capacities avoiding the free propagation of negative effects on interaction zones:

O1. **To identify Interaction Zones**: Spatiotemporal identification of airspace volumes in which two or more aircraft could co-exist. Those zones will be identified by the occurrence of a spatial and temporal concurrence events. A potential concurrence event occurs when the trajectories of two or more aircraft have a given probability to loss the separation minima (vertical or horizontal). The interaction zone spatiotemporal characterisation identifies the involved aircraft in the zone, the time stamp at which each aircraft enters in the zone and the time stamp at which each aircraft leaves the zone.

O2. **Identify Interaction Zones interdependencies**: Analysis of the spatiotemporal interdependencies among Interaction Zones. The coupling interdependency analysis of PARTAKE has been extended to evaluate the interaction zones interdependencies up and downstream. A coupling interdependency was defined in PARTAKE as the set of concurrent interdependencies happening at different areas when they involve, at least, one common flight.

O3. **Local and Distributed Interaction Metric**: existing sector entry and occupancy metrics are enhanced with the new interaction metrics that provide a spatiotemporal characterisation of the interaction Zones. These new metrics at a small volume granularity can be aggregated at sector level for better assessing the regulation efficiency. The analysis of the aggregated sector level interaction metrics considering also the dynamic interdependencies among sectors may provide a distributed ATFM model to avoid latent capacity due to the application of a local sector regulation without considering its possible impact on the rest of sectors.

O4. **Efficient Regulation support**: Present spatial airspace fragmentation together with a lack of integration of strategic, pre-tactical and tactical tasks is one of the main causes which constraints a proper coordination of regulation measures to mitigate the negative interdependencies of interaction zones. PARTAKE tools had been updated to enhance Demand Capacity Balancing with a visual supporting tool to interpret the positive and negative impact of upstream and downstream Interaction Zones dynamics as a guide for stabilizing the network effect.

In a nutshell, the scope of this project has been to demonstrate that it is possible to develop a data driven tool to analyse traffic at network level in order to identify and characterise the Interaction Zones and Hotspots, while considering the uncertainty in the flight trajectories. The following research questions have been addressed:

RQ1. How to identify interactions and characterise them as perceived by ATCO?

RQ2. How to identify clusters which represent interdependent interactions?

RQ3. How to take into account the uncertainty of the 4D trajectories to identify robust trajectory-based DCB measures?

RQ4. How to identify best flight candidates to apply trajectory revision measures to mitigate interactions?

RQ5. How to comprehensively display the information of interaction detection and analysis to the ATM actors?

RQ6. How to assess the impact of combined ATFCM/STAM measures to solve interactions?

RQ7. How to assess the interactions in direct link with density and complexity?

2.3 Research carried out

INTERFACING is an extension of the PARTAKE (SESAR ER2 project, GA: No. 699307) data driven methodologies ([1][2][3][4][5]) and its detection and analysis tools, to **implement new interaction metrics** for better integrating strategic and tactical information to detect ATC problems (i.e. potential co-existence in time of more than one aircraft in the same airspace volume) making use of the most up-to-date trajectory data (RBTs as published in DDR2 have been used in the experimentation scope of the project). The analysis tools extended in INTERFACING are enhanced with a macro level analysis of the interdependencies among interaction zones (either distributed through different sectors or spatially concentrated in the same sector) to enable a proper understanding of the spatiotemporal interdependencies among fragmented sector capacity constraints to avoid the propagation of undesired interaction-zone dynamics through the full ATM system together with the potential upstream and downstream negative effects of capacity regulations.

In order to answer research questions RQ1 to RQ4, which derive from objectives O1 and O2, a probabilistic framework for a formal definition and characterisation of the Interaction Zones, the Hotspots and their interdependencies has been established. In order to answer research questions RQ5 to RQ7, which derive from objectives O3 and O4, a demonstration toolkit including the algorithms supporting the concept and the visualisation tools has been implemented.

2.3.1 The INTERFACING probabilistic framework

Prior to establish the interaction metrics that will be used to assess the state of the airspace during a given time period, the following concepts are introduced:

- the **Characterisation** of the possible interaction that may exist during the analysed period,
- the **Existence Probability**, which is the probability that the interaction will occur,
- the **Complexity** of an interaction, which should measure its intrinsic properties and,
- the possible **Interdependencies** between the detected interaction.

The INTERFACING metrics will be calculated for a time interval defined as follows: at a given instant of time t_0, an assessment of the airspace state in the time period between the subsequent instant t_i (from seconds to hours after t_0) and the instant t_{i+th} is requested, where th represents analysis lookahead time. Thus, the metrics will quantify the airspace state during the time interval $[t_i, t_{i+th}]$ in terms of the concepts introduced above, which means that the metric values will dynamically change with time.

Previous definitions are complemented with the following concepts:

- **Uncertainty** in the position of an aircraft at a given instant can be projected into a volume in the space where that aircraft might be. Thus, given the planned 4D trajectory of an aircraft known at a time instant, the position of the aircraft is defined as a volume around the 3D point according to the planned trajectory at that instant. The non-disjoint union of the volumes that define the position of the aircraft at each instant of a given time interval defines the volume that contains all the positions where the aircraft should be during that time interval.
- An **Interaction Zone (*IZ*)** is an airspace region in which during a time interval there is the possibility that two or more aircraft are co-existing.
- An **Interdependence** between two *IZ*s is a relationship among them that can directly alter the *IZ*s, either its existence probability or its intrinsic properties. In other words, an interdependence between two *IZ*s is given when what happens in the one occurring first can influence in what happens in the one that occurs later.

These concepts have been formalised by a mathematical model capable to quantify in an unambiguous way the interaction metrics for the airspace assessment, including the capability to visualize in a graphical way all the information provided by the metrics.

Considering the spatiotemporal uncertainty in the predicted trajectory, the aircraft position is defined as the volume function of time:

$$\varphi_i(t): \mathbb{R} \longrightarrow U_i \subseteq \mathbb{R}^3$$

An orthohedron has been chosen as the shape of the volume $U_i \subseteq \mathbb{R}^3$, since its geometry can represent the different scales of uncertainty existing for each axis (see Figure 2).

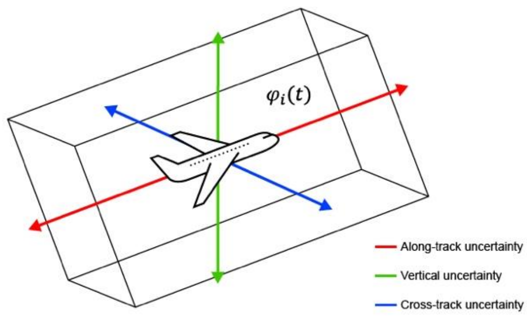

Figure 2. Representation of the spatial uncertainty of aircraft i at time t.

An interaction zone may involve two or more aircrafts. Two different concepts are introduced for this purpose: the Pairwise Interaction Zone (*P_IZ*) and the Generalized Interaction Zone (*G_IZ*). To identify the *P_IZ*s it is necessary to detect, for each instant within the analysed time interval $[t_i, t_{i+th}]$, all the non-empty intersections between the position functions of each possible pair of aircraft. A *P_IZ* exists during a given time interval, from now on I, between the first time when the intersection $\varphi_i(t) \cap \varphi_j(t)$ is not empty until the last moment fulfilling the same condition. Formally,

$$I = [t_{i+k}, t_{i+(k+l)}] \quad with \quad k + l \le th,$$

where

$$\varphi_i(t) \cap \varphi_j(t) = \begin{cases} \emptyset & \forall t < t_{i+k} \\ V \subseteq \mathbb{R}^3, \quad V \neq \emptyset, & \forall t \in I \end{cases}$$

The non-disjoint union of the volumes $\varphi_i(t)$ for every time t within the interval I defines the volume where the aircraft i is going to be with probability 1 during the course of the *P_IZ*.

Let $\Phi_i(I) = \bigcup_{t \in I} \varphi_i(t)$ be a spatial volume over a time interval I, then the spatial volume that defines the *P_IZ* is determined by the intersection $\Psi_{i,j}(I) = \Phi_i(I) \cap \Phi_j(I)$, as illustrated in Figure 3.

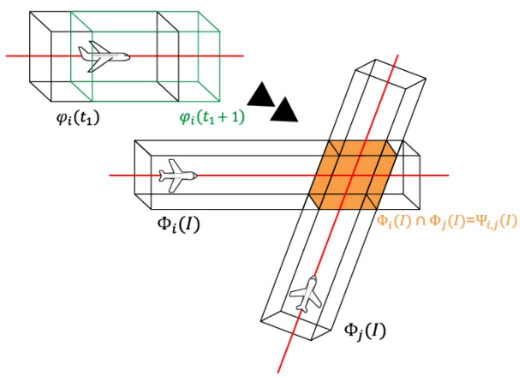

Figure 3. In orange, the spatial volume that defines the P_IZ.

To be computationally practicable, this process requires a discretization both in time and space and also the use of techniques to discard pairs of aircraft (i, j) that, because of their distance, it is obvious that the intersection $\varphi_i(t) \cap \varphi_j(t)$ is empty for any instant $t \in [t_i, t_{i+th}]$ (an algorithm based on PARTAKE functionalities for detecting potential concurrence events has been used for this filtering purpose).

The spatiotemporal formalisation of a *P_IZ* is now complemented with its existence probability. Let t_0 be the last time actual trajectories were updated. Let $\varphi_i^{t_0}: [t_0, t_{f_i}] \subset \mathbb{R} \longrightarrow \mathbb{R}^3$ be the position function describing the volume in space where the aircraft i is located with probability one at a given time $t \in$

$[t_0, t_{f_i}]$, being t_{f_i} the arrival time of aircraft i. Note that the function depends on t_0, so it dynamically changes according to most up-to-date aircraft's position at t_0. The Figure 4 illustrates this concept that shows the INTERFACING framework would benefit from a TBO context where flight trajectories are continuously updated.

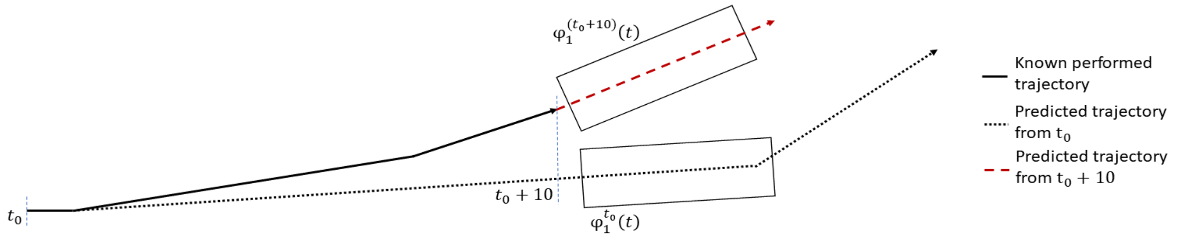

Figure 4. The aircraft AC1 is performing a different trajectory that the one predicted at time t_0. When updating the information 10 seconds later, at $t_0 + 10$, it does not make sense to keep using the position function $\varphi_1^{t_0}(t)$ since it is known to be wrong thanks to the most recent trajectory update.

Let $p_1^{t_0}(t, \vec{x})$ be the probability density function (pdf) at time t for AC1 that determines the probability of the aircraft being located at a point $\vec{x} \in \varphi_1^{t_0}$ at time t. Figure 5 illustrates the multivariate Gaussian pdf used at experimental exercises.

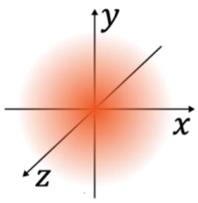

Figure 5. Representation of a multivariate Gaussian distribution with three dimensions. A density function takes values at each point in space, in this case, the maximum is in the centre, and the values decrease as the distance from the centre increases.

The higher the lookahead time of a prediction is the more dispersed the non-zero values of the pdf should be. This is a representation of how uncertainty increases as the lookahead increases due to the possibility that the aircraft does not follow the trajectory predicted at a given time. The Figure 6 illustrates this concept: at t_1 the probability is more centred since for a close lookahead time, is less probable that the aircraft has gone too far from its predicted trajectory, while at t_2 the probability is more sparse and with lower values since it gets harder to predict at which point of $\varphi_1^{t_0}$ the aircraft will be.

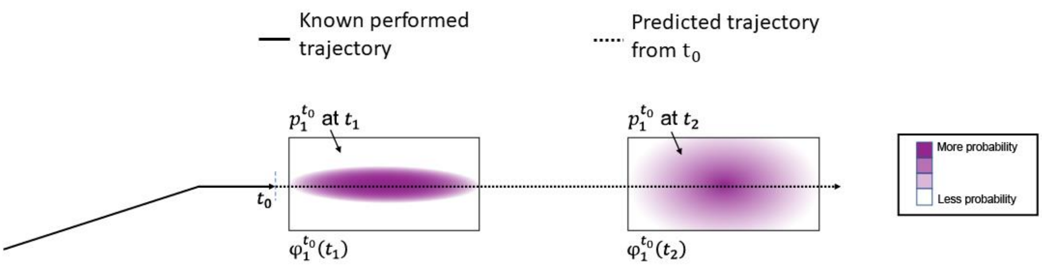

Figure 6. Example of the uncertainty's lookahead dependency.

Furthermore, the pdf functions also depend on t_0 in a similar way as the volume function $\varphi_i^{t_0}$ (see Figure 4), since the last known location of the aircraft directly affects the predictions of where it is going to be. Thus, the values of the pdf also change in time and space as Figure 7 illustrates. For readability of the text, t_0 will be in general omitted when there is no reason for clarification.

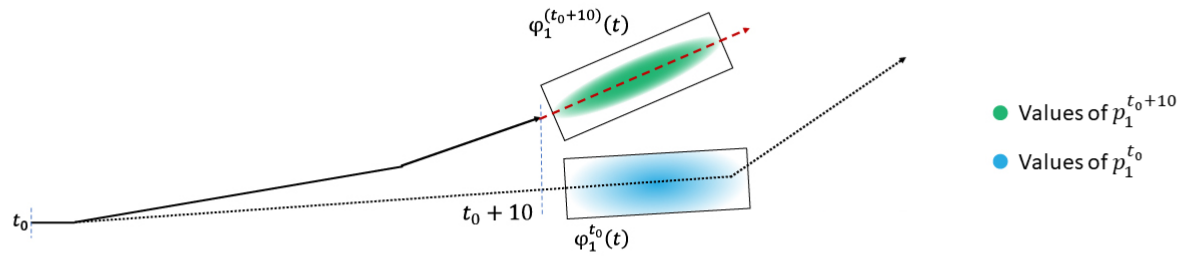

Figure 7. The pdf from t_0 is obsolete once the information about the aircraft is updated at $t_0 + 10$.

The *P_IZ* existence probability can be now calculated as follows. Consider two aircraft, AC1 and AC2, and their volume functions, φ_1 and φ_2 respectively. For a fixed time t, the probability of AC1 and AC2 being at the same airspace region is that of AC1 and AC2 being at the intersection between φ_1 and φ_2 (if any) as illustrated at Figure 8.

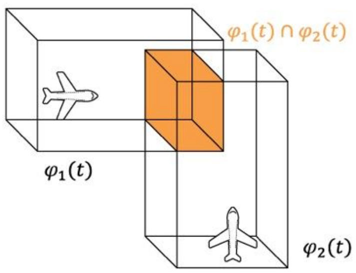

Figure 8. The intersection of the volume functions at time t is an airspace volume where the aircrafts might coexist.

Let $p_1(\mathrm{t}, \vec{x})$ and $p_2(\mathrm{t}, \vec{x})$ be the probability density functions (pdf) at time t of AC1 and AC2 respectively. The integral of these functions over a volume yields the probability of the aircraft being inside that volume at that specific time:

$$\int_{\varphi_1(t)} p_1(\mathrm{t}, \vec{x}) d\vec{x} = \int_{\varphi_2(t)} p_2(\mathrm{t}, \vec{x}) d\vec{x} = 1$$

Hence, the probability of AC1 and AC2 being inside the shared volume $\varphi_1(t) \cap \varphi_2(t)$ can be computed as:

$$\mathrm{EP(t)} = \int_{\varphi_1(t) \cap \varphi_2(t)} p_1(t, \vec{x}) d\vec{x} \cdot \int_{\varphi_1(t) \cap \varphi_2(t)} p_2(t, \vec{x}) d\vec{x}$$

where $\mathrm{EP(t)}$ is the interaction existence probability, which is the probability of AC1 and AC2 coexisting in the shared volume $\varphi_1(t) \cap \varphi_2(t)$ at a time t.

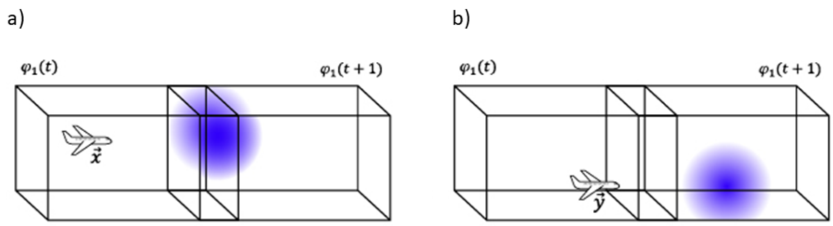

Figure 9. If time dependency is not ignored, then a pdf should be considered for each point from the initial uncertainty volume.

Existence probability at two different time instants are dependent events, that is, $EP(t)$ directly affects the value of $EP(t + 1)$. But if these dependencies were to be considered, each point in the initial uncertainty volume would lead to uncountable possibilities, each one leading to even more scenarios, causing the computational cost to be unaffordable. The Figure 9 illustrates this issue.

As an alternative, the use of estimators based on the complement of probability is proposed. Let $\mathrm{EP}^c(\mathrm{t}) = 1 - \mathrm{EP}(t)$ be the probability complement, that is, the probability of no-coexistence situation at time t between aircraft AC1 and AC2 inside the shared volume. The complementary probability of not coexisting at any instant of time during a fixed time interval I is proposed as an estimator for the probability of a coexistence situation occurring at some instant in I. In formulas, given the time interval $I = [t_1, t_2]$ of the *P_IZ*, the probability of an interaction during I is computed as follows:

$$\mathrm{P_u}(I) = 1 - \prod_{t \in I} \mathrm{EP^c}(t)$$

This estimator should be considered as an upper bound for the actual probability of coexistence. This is due to the fact that physically unfeasible trajectories[1] are being considered to avoid a computational explosion when lengthening the interval I. On the other hand, the lower bound estimator is proposed:

$$P_l(I) = \max_{t \in I}\big(EP(t)\big),$$

which does not count for unfeasible trajectories, but it does not manifest the actual probability of the whole interval since it's only the computed value of one instant of time. Both estimators will be more precise for shorter time intervals and increase the error as the interval I gets longer. The reason for this is that the longer the interval is, the more impossible trajectories are being considered for the upper bound and the more information is missed in the lower bound.

Thus, the existence probability is not an exact value but an interval that contains it. When the upper and lower bounds are really close to each other, they form a small interval which provides a good estimation of the exact value of the probability. Otherwise, it becomes more difficult to know where the existence probability lays as lower and upper bound range gets wider, i.e., the statistical confidence on the P_IZ existence decreases as the probability interval increases.

The *Generalized Interaction Zone* (*G_IZ*) extends the concept of Pairwise Interaction Zone (*P_IZ*) by representing an interaction involving two or more aircraft. This concept arises naturally from the understanding that in real scenarios co-existence situations where more than two aircraft are involved may occur. Formally defined, a *G_IZ* is the result of one single *P_IZ* or a combination of several *P_IZ*s which, in this case, interact with each other in different ways. Therefore, the spaciotemporal characterisation of a *G_IZ* is built from the spaciotemporal characterisations of the *P_IZs* composing the *G_IZ*. The situation depicted at Figure 10 will be considered in order to illustrate how the *G_IZ* spatiotemporal relationships and their existence probability are characterised from the *P_IZs* component characterisation.

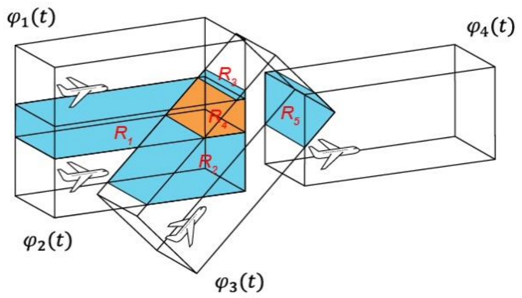

Figure 10. Example of an Interaction Zone with four aircrafts.

[1] In this context, it refers to a trajectory which can't be flown by an aircraft (e.g. disconnected in time, with sudden and abrupt changes in heading, etc.)

At this particular situation, four *P_IZs* are detected and they are not independent since they share, at least, one aircraft, they have non-empty intersecting volumes (R_i labelled at Figure 10) and, finally, they have overlapping existence intervals, as illustrated by the time intervals in Figure 11.

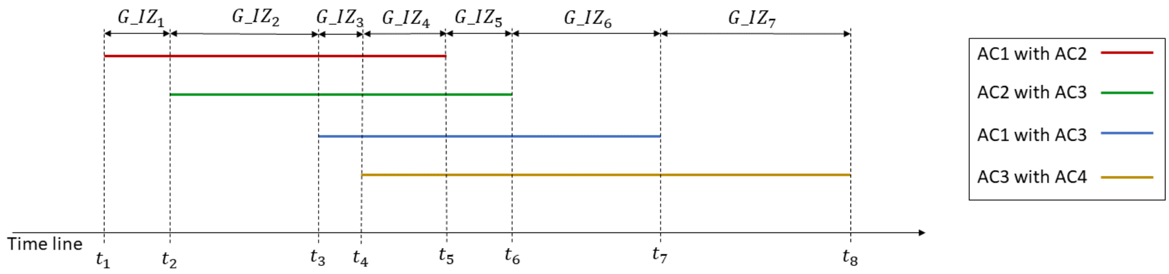

Figure 11. Example where four interdependent pairwise interactions. The figure represents the time intervals where these interactions happen and the emerging G_IZs.

In detail, the temporal characterisation in Figure 11 show that these four *P_IZ* are not independent, since there are aircrafts participating at the same time in more than one *P_IZ*. The temporal characterisation of a *G_IZ* arises from these *P_IZ* interdependencies. As it can be seen in Figure 11, the interactions evolve in the following way, at the beginning AC1 and AC2 are interacting. At t_2, AC3 starts interaction with, AC2 while AC2 stills interacts with AC1, and so on so for. From this temporal view, a *G_IZ* exists while the *P_IZ* member do not change, and a new *G_IZ* emerges when new *P_IZ*, with at least one common aircraft, comes to or leaves the game. According to this view, seven *G_IZs* are present in the example.

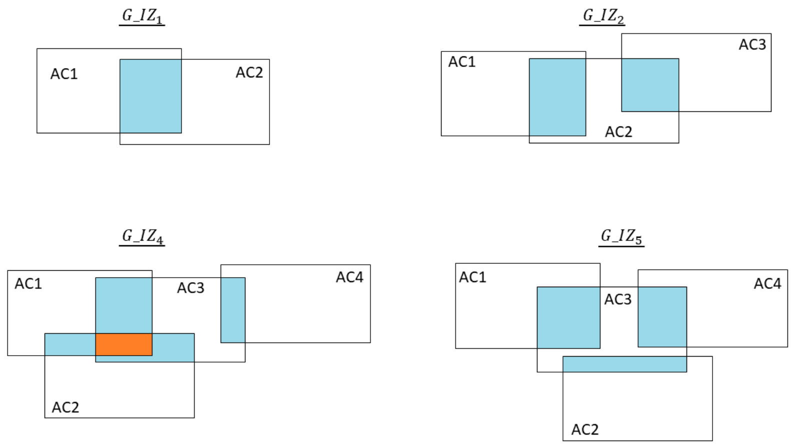

Figure 12. Examples of spatial characterisations of some of the detected G_IZs (planar representation is chosen for the sake of simplicity).

In order to complete the *G_IZ* definition, the spatial view is required. For instance, looking at G_IZ_2 in Figure 12, where three aircrafts are involved, it happens that $\Phi_1(I_2) \cap \Phi_2(I_2) \cap \Phi_3(I_2) = \emptyset$ during the interval $I_2 = [t_2, t_3)$, so the three aircrafts that compose the *G_IZ* will never share a given space volume during I_2, although pairwise $\Phi_i(I_2) \cap \Phi_j(I_2)$ coexist at some time in I_2. However, during the interval $I_4 = [t_4, t_5)$, $\Phi_1(I_4) \cap \Phi_2(I_4) \cap \Phi_3(I_4) \neq \emptyset$ so aircrafts AC1, AC2 and AC3 could eventually share a non-empty region.

Therefore, the spatial characterisation of a *G_IZ* with three aircraft as the intersection $\Phi_1(\mathrm{I}) \cap \Phi_2(\mathrm{I}) \cap \Phi_3(\mathrm{I})$ might occasionally be inaccurate and misleading. Alternatively, a more conservative approach has been chosen by defining the spatial characterisation of a *G_IZ* with three aircraft as the non-disjoint union between the three pairwise intersections: $\Phi_1(\mathrm{I}) \cap \Phi_2(\mathrm{I})$, $\Phi_1(\mathrm{I}) \cap \Phi_3(\mathrm{I})$ and $\Phi_2(\mathrm{I}) \cap \Phi_3(\mathrm{I})$.

The *G_IZ* temporal existence can be formalised as follows. Let $\mathcal{P}(I)$ be the set of *P_IZ* existing over a given time interval I and let be the interval $I_k = [b_k, b_{k+1}) \subseteq I$. Let $\alpha(t)$ be a function that calculates the number of intersections between pairs of position functions $\varphi_i(t)$ at time t such that

$$\bigcup_{i \in \mathrm{A_k}} \varphi_i(t) = \mathrm{V}$$

being A_k the index set of the intersecting position functions and V a path-connected space. This last condition implies that for every two points $\vec{x}, \vec{y}$ in V there exists a continuous path entirely contained in V that connects $\vec{x}$ and $\vec{y}$. In practise, this means that the resulting intersection spaces share at least one aircraft (see coloured areas in Figure 12).

Finally, the interval $I_k$defines the existence period of a *G_IZ* if and only if:

$$\alpha(\mathrm{t}) = \mathrm{c}_k \ \ \forall \mathrm{t} \in \mathrm{I_k} \quad and \quad \alpha(\mathrm{b_k} - 1) \neq \mathrm{c}_k \ \neq \alpha(\mathrm{b_{k+1}} + 1)$$

where c_k is an integer value.

In general, given a $G\_IZ = \{P\_IZ_1, P\_IZ_2, \cdots, P\_IZ_n\}$, where the aircraft pairs are indexed in a natural order, and the existence time interval I, the air space volume corresponding to the *G_IZ* is given by:

$$\Psi(I) = \bigcup_{i=1}^{n} \psi_i(I)$$

By applying this spatiotemporal characterisation to the example shown in Figure 11 and Figure 12, seven *G_IZ* existence intervals example I_k: $k = 1..7$ are found. Each *G_IZ* in the example represents:

- $\mathrm{G\_I}Z_1$: Only the *P_IZ* with AC1 and AC2 involved has started.
- G_IZ_2: Two *P_IZ*s happening at the same time, the first one between AC1 and AC2, the second one between AC2 and AC3. AC2 may coexist with AC1 or AC3.
- $\mathrm{G\_I}Z_3$: Three *P_IZ*s happening at the same time, AC1 with AC2, AC2 with AC3 and AC1 with AC3. In case these *P_IZ*s intersect with each other, there might be an airspace region where the three aircraft coexist at the same time.
- G_IZ_4: Four *P_IZ*s. Like the previous one, these *P_IZ*s might coexist or might not.
- G_IZ_5: The AC1 and AC2 *P_IZ* has ended and the other three *P_IZ*s remain.
- $\mathrm{G\_IZ}_6$: Two *P_IZ*s remain.
- $\mathrm{G\_IZ}_7$: Only the AC3 and AC4 *P_IZ* remains, the others have already ended.

By focusing on the G_IZ_4, its existence interval is $I = [t_4, t_5)$. The space volume for each *P_IZ* member during I is given by:

$$\psi_{1,2}(I) = \Phi_1(I) \cap \Phi_2(I),$$

$$\psi_{1,3}(I) = \Phi_1(I) \cap \Phi_3(I),$$

$$\psi_{2,3}(I) = \Phi_2(I) \cap \Phi_3(I),$$

$$\psi_{3,4}(I) = \Phi_3(I) \cap \Phi_4(I)$$

where $\Phi_i(I) = \bigcup_{t \in I} \varphi_i(t)$. So, the volume for G_IZ_4 is $\Psi(I) = \psi_{1,2}(I) \cup \psi_{1,3}(I) \cup \psi_{2,3}(I) \cup \psi_{3,4}(I)$.

In order to complete the characterisation of the Generalized Interaction Zone, its existence probability follows the approach analogous to the existence probability on a Pairwise Interaction Zone. The lower and upper bounds of the *EP* probability is computed for each region $\psi_{i,j}(I)$ where two or more position volumes intersect. Just like in the pairwise case, the first part of the analysis is for a fixed instant of time t.

In the example from Figure 10, the probability should be computed for regions R_1, R_2, R_3, R_4 and R_5. In each region, the sum of the probabilities of all the possible interactions returns its specific *EP*. For example, in R_1 there is only one possible interaction, AC1 with AC2, so its specific probability would be

$$EP(\mathrm{R}_1) = \int_{R_1} p_1(t,\vec{x})d\vec{x} \cdot \int_{\mathrm{R}_1} p_2(t,\vec{x})d\vec{x}$$

as the pairwise case. Regions R_2, R_3 and R_5 are analogous to R_1. Region R_4 is the result of an intersection of three position functions with a combination of four possible interactions:

- A triple interaction with AC1, AC2 and AC3 altogether in R_4.
- A pairwise interaction with AC1 and AC2 where AC3 is outside R_4.
- A pairwise interaction with AC1 and AC3 where AC2 is outside R_4.
- A pairwise interaction with AC2 and AC3 where AC1 is outside R_4.

The sum of the probabilities of these interactions yields the existence probability for R_4:

$$\begin{aligned} EP(\mathrm{R}_4) = &\int_{\mathrm{R}_4} p_1(t,\vec{x})d\vec{x} \cdot \int_{\mathrm{R}_4} p_2(t,\vec{x})d\vec{x} \cdot \int_{\mathrm{R}_4} p_3(t,\vec{x})d\vec{x} + \\ &+ \int_{\mathrm{R}_4} p_1(t,\vec{x})d\vec{x} \cdot \int_{\mathrm{R}_4} p_2(t,\vec{x})d\vec{x} \cdot \int_{\varphi_3(\mathrm{t})\setminus R_4} p_3(t,\vec{x})d\vec{x} + \\ &+ \int_{\mathrm{R}_4} p_1(t,\vec{x})d\vec{x} \cdot \int_{\varphi_2(\mathrm{t})\setminus \mathrm{R}_4} p_2(t,\vec{x})d\vec{x} \cdot \int_{\mathrm{R}_4} p_3(t,\vec{x})d\vec{x} + \\ &+ \int_{\varphi_1(\mathrm{t})\setminus R_4} p_1(t,\vec{x})d\vec{x} \cdot \int_{\mathrm{R}_4} p_2(t,\vec{x})d\vec{x} \cdot \int_{\mathrm{R}_4} p_3(t,\vec{x})d\vec{x} \end{aligned}$$

For the general case, the *G_IZ* airspace volume is divided in regions depending on how many position functions are intersecting. Let $PR = \{\mathrm{R}_1, \mathrm{R}_2, \cdots, \mathrm{R}_n\}$ be the set of all airspace regions formed by at least one intersection and $PF_i = \{\varphi_1, \varphi_2, \cdots, \varphi_k\}$ for $i = 1,2,\cdots,n$ be the corresponding position functions to region R_i. Consider the family of sets $U_i = \{\mathrm{S} \in \mathcal{P}(PF_i) \mid |\mathrm{S}| \geq 2\}$ and the family of functions

$$\mathbb{1}_S(j) = \begin{cases} 1 & if \quad \varphi_j \in S \\ 0 & if \quad \varphi_j \notin S \end{cases}$$

Then, the coexistence probability at time t is for region Ri

$$\mathrm{P}(R_i) = \sum_{S \in U_i} \left(\prod_{j=1}^{|PF_i|} \left(\left(\mathbb{1}_S(j) \int_{R_i} p_j(t,\vec{x})d\vec{x} \right) + \left(\left(1 - \mathbb{1}_S(j)\right) \int_{\varphi_j \setminus R_i} p_j(t,\vec{x})d\vec{x} \right) \right) \right)$$

where $|PF_i|$ is the cardinality of PF_i. Finally, the existence probability of the entire *G_IZ* at time *t* combines the probabilities between regions:

$$\mathrm{EP(t)} = \bigcup_{i=1}^{n} P(R_i)$$

As for the existence probability of the time interval *I*, the same procedure for the upper and lower bound in the pairwise case shall be followed:

$$\mathrm{P_u}(I) = 1 - \prod_{t \in I} \mathrm{E}P^c(t),$$

$$P_l(I) = \max_{t \in I} EP(t)$$

Note that the aircrafts shared among several *G_IZ* create the interdependencies among them. By definition, interdependent *G_IZ* form a time ordered sequence. Thus, any action taken on an early *G_IZ* might impact to the subsequent interdependent G_IZs. For instance, a flight regulation on AC3 in the example (see Figure 10) can remove the triple interaction at R_4 and, therefore, significantly alter all detected *G_IZs*, to the point that some might eventually disappear (e.g. *G_IZ* 5, 6 and 7).

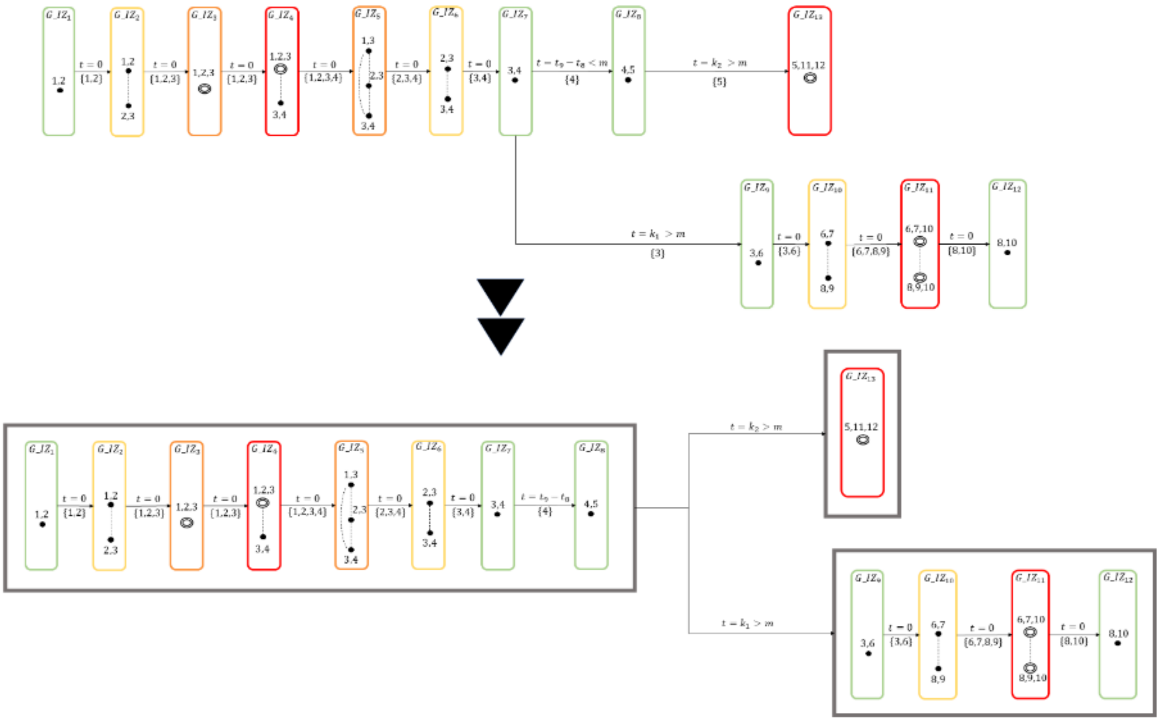

Figure 13. Example of a G_IZ interdependency graph (upper picture) clustered into hot spots for a given time threshold m (lower picture).

In order to exploit the potential benefits of this kind of information, INTERFACING proposes a macro-analysis approach based on the concept of Hotspot. The macro-analysis purpose is to identify those flights creating the interdependencies for selection the best candidates to apply trajectory revision measures to solve interactions (e.g. flight regulation or departure synchronization measures for grounded flights similar to the mitigation measures proposed in PARTAKE).

An interdependency graph is built for this purpose. The graph nodes represent the detected G_IZ and the edges the interdependencies among them (see upper graph in Figure 13). The edges are qualified with an attribute whose value is the time separation between two interdependent *G_IZ*. A Hotspot is defined as an aggregation of Interaction Zones sharing at least one A/C and happening in time intervals separated below a given threshold m, with a maximum value equals to the analysed period of time.

Therefore, given the threshold m, the hotspots are identified by a clustering algorithm that groups *G_IZs* when the time attribute of the interdependency edges connecting them is below the given threshold. An example is illustrated in the lower graph in Figure 13, where three hotspots are identified for a value m. The shorter the threshold is, the more localized the hotspots are. Hotspots and their interdependencies at network level can be observed by increasing the threshold value. As the threshold increases, the more local G_IZs are grouped in a single hotspot and the more distanced interdependencies are identified (see Figure 14).

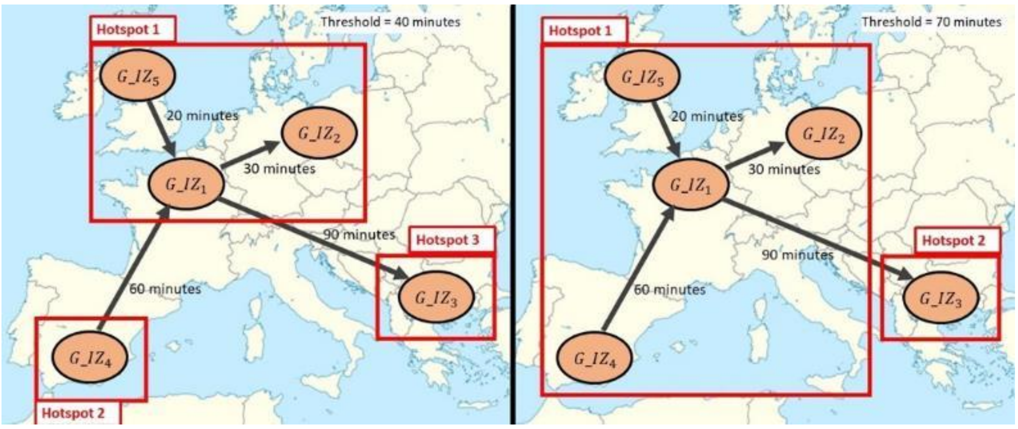

Figure 14. A scenario of G_IZs grouped in Hotspots with different Hotspot Time Separation values. On the left: A threshold of 40 minutes. On the right: A threshold of 70 minutes.

The proposed metrics aims at providing relevant indicators for the airspace state assessment in terms of the Interaction Zones and related Hotspots. These metrics will provide information about the *G_IZ* and their intrinsic properties and about how the *G_IZ*s connect with each other for a better assessment with different geographical focus (from local to network wide).

The spatial and time characterisation and the existence probability and the complexity will be used to create metrics, comprehensive in terms of the quantitative a valuation and also in terms of visualisation:

- **M1 Spatiotemporal characterisation**: the time interval when a G_IZ occurs and the airspace location where it happens. This metric corresponds to the spatiotemporal characterisation elaborated in the probabilistic framework.
- **M2 Existence probability**: the probability that a G_IZ actually occurs is a value between 0 and 100 to represent the probability (as a percentage). For example, a G_IZ with M2=5% means it has a low existence probability, thus it may never occur, but a G_IZ with M2=98% suggests that the aircrafts involved are highly likely going to interact.
- **M3 Number of aircraft involved**: an integer value greater than 1 to represent how many aircraft are interacting in a G_IZ. For instance, a G_IZ with M3=4 means there are a total of 4 aircraft in the zone.
- **M4 Complexity**: complexity is proposed as a measure of the intrinsic structure of the *G_IZ*, i.e., how many pairwise interactions contain and how they interact among them. combined with the existence probability. This metric provides a value greater or equal to zero, the greater this value is, the more complex a *G_IZ* is.

The previous metrics can be **aggregated** for airspace volumes instead of just focusing on a single *G_IZ*. For example, an airspace sector could be analysed with the aggregated information of all the *G_IZ*s it contains.

The following group of metrics are computed from the macro-level analysis of interdependencies, from local to network wide depending on the threshold set for the hotspot clustering:

- **M5 Elapsed time of the hotspots**: gives an intuitive measure about the magnitude of related interaction zones, both in terms of duration (minutes) and involved flights. When a hot spot lasts for too long, the involved flights should be analysed to design proper mitigation measures ('too long' is an operational parameter that must be defined by ATM actors). The main objective for this metric is to help ATM assessing the priority of different hot spot. For example, assume 6 hot spots are predicted, 5 of them last around 4 minutes, and the sixth one lasts for 30 minutes. ATM may decide to focus on the latter due to M5 is much higher.

- **M6 Time separation between hot spots**: this metric (time in minutes), along with M7, is useful to identify which measures are available to execute in order to mitigate the interaction zone.
- **M7 Which and how many aircraft are shared from one hot spot to another**: is a list of the flights shared by more than one hot spot and an integer representing the list size (number of flights). Along with M6, can be useful to decide in which flights corrective measures should be focused and what is the best approach to do so.
- **M8 Areas where a high number of hot spots tend to happen recurrently**: gives a spatial view of which airspace regions commonly are prone to have interaction zones and where extra attention is required.

Table 1: Relation between objectives and their related metrics

Objectives	Metrics
O1 To identify Interaction Zones	M1, M2, M3, M4
O2 Identify Interaction Zones interdependencies	M5, M6, M7
O3 Local and Distributed Interaction Metric	M2, M3, M4, M8

Table 1 relates the previous metrics with the project objectives O1 to O3. For the objective O4 (Efficient Regulation support), the impact assessment by scenario analysis of applied mitigation measures can be performed with the developed toolkit. The consequences of applying a measure can be simulated to assess if the predicted situation improves in preventing the *G_IZ*s or if it turns out to worsen the situation.

2.3.2 The Demonstrator toolkit

An important part of the INTERFACING project has been the algorithmic implementation of the probabilistic framework for Interaction Zone detection and characterisation. The summary of main algorithms is described in Table 2.

Table 2: INTERFACING algorithms and brief descriptions.

INTERFACING algorithms	Description
Concurrence Event Detection	PARTAKE returns the segment of the trajectories where a potential loss of separation may occur.
Enveloping Computation	Given a trajectory planification and an interval of time, this algorithm creates the envelope (the position function) for each instant of time in the interval.
P_IZ Computation	This algorithm analyses the potential concurrent events returned by PARTAKE and, by using the envelopes returned from the previous step, creates *P_IZ*s when the envelopes intersect.
P_IZ Clustering	This algorithm creates *G_IZ*s from *P_IZ*s and places them in time, as described in section 2.3.1. All found *P_IZ*s are analysed and those *P_IZ*s that share aircraft at same time are grouped together in *G_IZ*s.
Interdependencies	All found *G_IZ*s are studied in order to connect every pair of them that have at least a participating aircraft in common. Then, for each of these connections, the elapsed time between the connected G_IZs is computed.

Spatial Computation	Given a *G_IZ* and an instant of time, this algorithm finds an approximation of the airspace 3D shape where the envelopes of the participating aircraft intersect. To do it, the algorithm makes use of an octree to approximate the mentioned airspace volume with voxels.
Metrics 1, 2, 3 and 4 Computation	Given a *G_IZ*, the time interval when it happens and its spatial location approximated by voxels, this algorithm integrates the voxels and computes the existence probability for each instant of time in the interval. Then it computes the existence probability lower bound, upper bound and the complexity of the overall *G_IZ*.
G_IZ Clustering	This algorithm analyses all *G_IZ*s interdependencies and groups together all those *G_IZ*s which occur closer in time than a given threshold. The created groups are Hotspots.
Metrics 5, 6 and 7 Computation	Given all found Hotspot, this algorithm computes the elapsed time for each one along with the time between connections and its shared aircraft.

The aforementioned algorithms are combined and work together to create the main algorithm of INTERFACING. The order in which these algorithms are executed and how they interact with each other is shown in Figure 15.

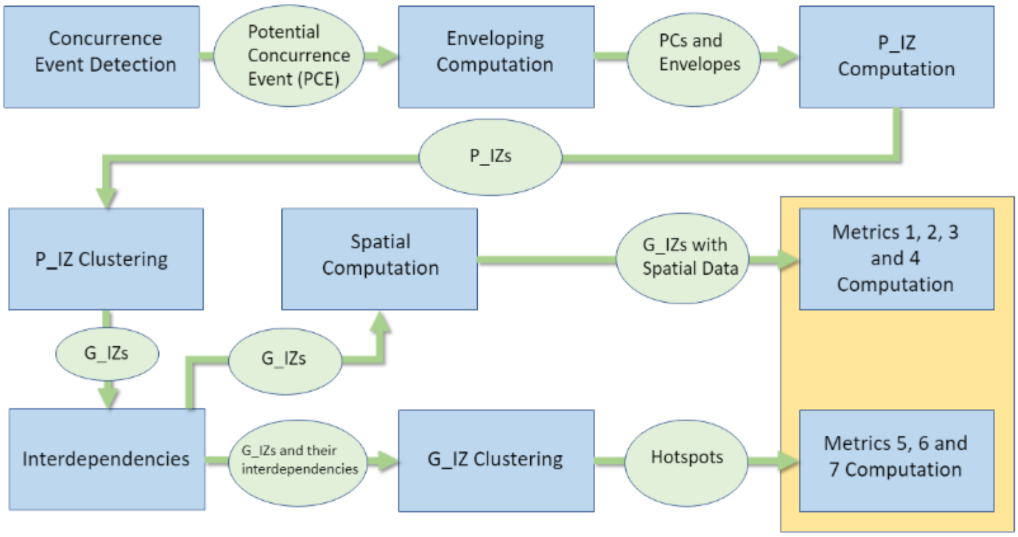

Figure 15. INTERFACING algorithms workflow.

INTERFACING algorithms have some tuning parameters for configuring different setups, providing customization depending on the preferences when executing the algorithm. These parameters are the following:

- **Current Time and detection window:** The *Current Time* parameter *t0* stands for the last instant of time that the information about trajectories was updated. Thus, the aircraft location at time *t0* is the last one known. The *Detection Window* is the time interval in which INTERFACING analyses the aircraft position uncertainty and looks for *G_IZs*. The more advanced in time the *Detection Window* is from *t0*, the greater the predicted location uncertainty is. See Figure 16 for an example.
- **Along-track, Cross-track and Vertical distances:** These parameters define the dimensions of the orthohedron used for the position functions φ_i. As shown in Figure 2, the along-track distance is the length of the orthohedron in the direction the aircraft is headed, the vertical distance is the orthohedron height and the cross-track distance is the orthohedron length in the perpendicular direction to both the along-track and the vertical directions.

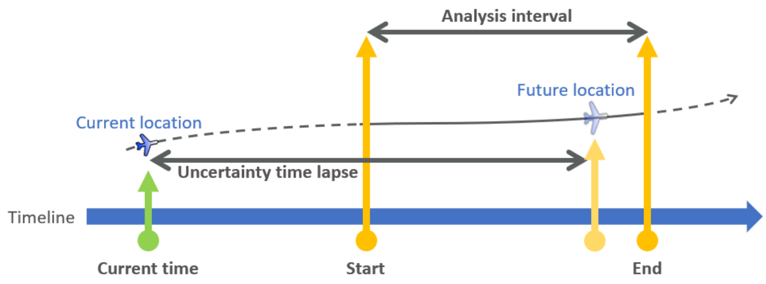

Figure 16. Visual example of the Current Time and Detection Window parameters. The uncertainty time lapse determines how big is the resulting probability, the greater the uncertainty is, the lower is the probability.

- **Envelope accuracy:** Due to earth's curvature, a normal orthohedron does not provide the best accuracy when describing the aircraft possible location (see Figure 17). The parameter *Envelope Accuracy* provides the option to discretise the orthohedron in subsections in order to bend it and follow the earth curvature. Discretising the orthohedron makes the algorithm much more precise and offers better results, but it also increases the amount of computation the algorithm must do making it slower.

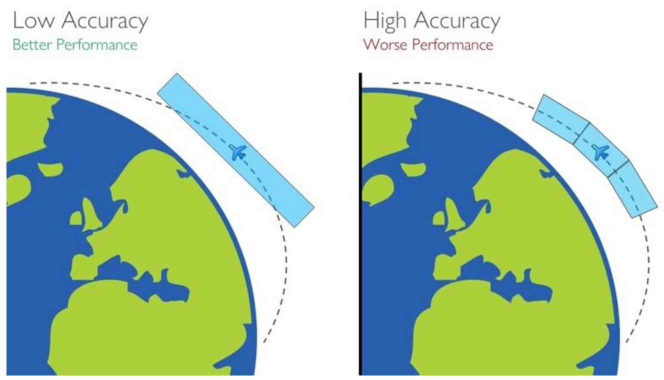

Figure 17. Example of the Envelope Accuracy parameter. The higher accuracy, the longer it takes for the algorithm to make the computations.

- **Hotspot Time Separation:** *Hotspot Time Separation* is the threshold *m* described previously, which is used to decide when two *G_IZ*s are clustered in the same Hotspot.

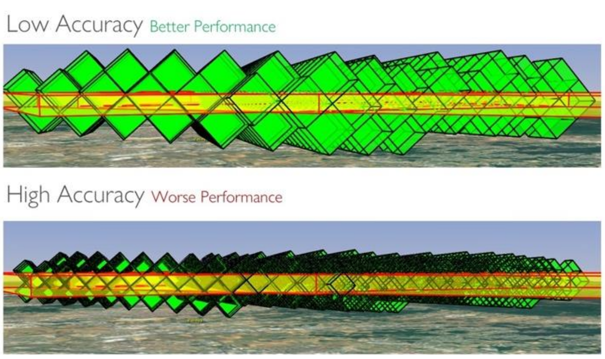

Figure 18. Example of the Spatial Discretization parameter. For smaller values, voxels are smaller too and are able to describe a determined airspace with much more precision.

- **Spatial discretization accuracy:** This parameter describes the minimum length of the voxels used to discretise the intersections. The algorithm is more precise if this parameter has lower values, since smaller voxels are able to describe a determined air space much better than larger ones. On the other hand, if voxels are smaller, it requires many more voxels to approximate the target area which implies more computations and greatly increases the number of operations require, worsening the time performance of the algorithm. See *Figure 18* for an example.

- **Temporal discretization accuracy:** This parameter is used to discretise the time interval described by the detection window in order to reduce the number of calculations. This is done by skipping some of the instants of time instead of analysing the whole interval and use interpolation methods to assign values to the skipped times. This makes the algorithm much faster, but the more instants of time that are skipped the more information is lost, thus the results are less precise.

2.4 Results

Apart from the formalisation of the probabilistic framework, the main output from the project has been the release of the *DEM.1 Demonstration Tool*. A detailed description of the various INTERFACING software components is provided in deliverable R.2*: Verification and Validation report*. In brief, these are the components composing the demonstration tools:

- INTERFACING toolkit: is the core of the project developments. It is a library of functional blocks that works as a pipeline, taking the traffic scenario as the main input, along with the algorithm tuning parameters, and producing the results of the interaction zone analysis. The traffic scenario is described by the set of 4DT trajectories using the so6 format. The analysis results are represented by a complex data structure (using a new format called VisioJSON, which extends from GeoJSON) containing the detected interaction zones, hotspots, their metrics as well as their interdependencies, according to the concepts and definitions that were introduced in the concept of operations.
- AsloEarth: is a visualisation tool created as part of the INTERFACING project to graphically show the objects and metrics produced by the interaction zone analysis. For example, animated trajectories, interaction spaces and other metrics (see Figure 19).

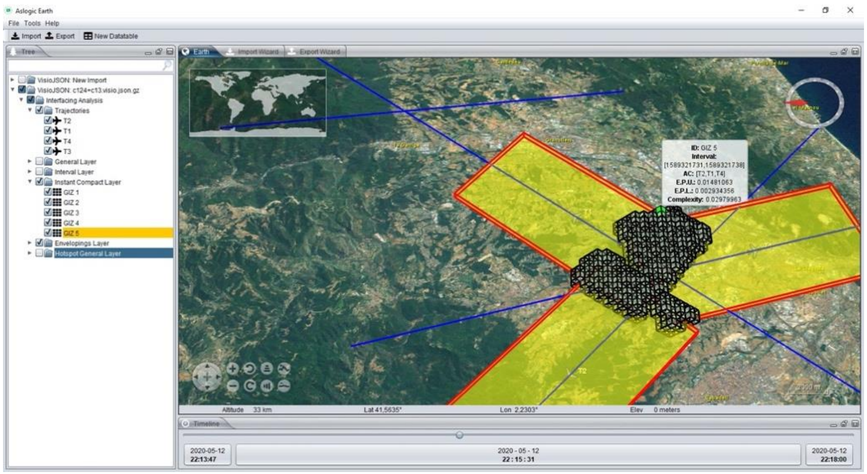

Figure 19. AsloEarth visualisation tool.

- R-NEST plugin. NEST and R-NEST are the reference tools in ATM for the analysis of air traffic scenarios. A software communication interface for ordering executions and sending scenarios between the R-NEST and the module INTERFACING was designed and, at the moment of writing this report, is completing its development (see Figure 20). Therefore, ATM community will benefit from the project outcomes through the R-NEST platform.

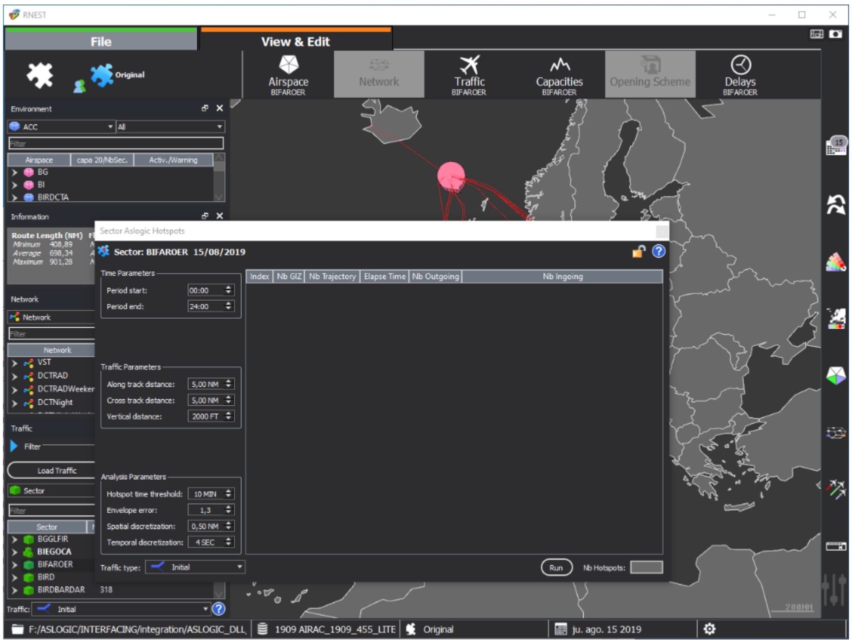

Figure 20. R-NEST instance with the INTERFACING parameters window opened

The result of executing the INTERFACING toolkit, the spatial objects and the metrics supporting the Interaction Zone (*G_IZ*) evaluation, can be visualized as follows[2]:

- **Spatiotemporal characterisation (M1)**: A *G_IZ* appears when the intersection of the envelopes predicting future position of two or more aircrafts is not empty (see envelop layer at Figure 21). The instant layer shows the *G_IZ*s at each time instance (see Figure 22). It is a *G_IZ* snapshot showing the voxelated intersected area and the *G_IZ* metrics in a time instant. The whole *G_IZ* spatial characterisation is visualized as heatmap with the voxels (see Figure 23). The *G_IZ* geometry is represented in this layer and the voxel colours are determined by the complexity metric in a scale ranging from white to black. The total duration of a *G_IZ* is shown in its info box (see Figure 24).
- **Existence probability (M2**): The existence probability interval of a *G_IZ* is shown in its info box (see Figure 24).
- **Number of aircraft involved (M3**): The number of involved aircrafts in the *G_IZ* is shown in its info box (see Figure 24).
- **Complexity (M4**): The value of the *G_IZ* complexity is shown in its info box (see Figure 24).
- **Elapsed time of the hot spots (M5)**: Hotspots are represented by the layer described in Figure 25.
- **Time separation between hot spots (M6)**: the time in minutes is shown in the hotspot interdependency info box (see Figure 28).
- **Which and how many aircraft are shared from one hot spot to another (M7)**: is shown in the hotspot interdependency info box (see Figure 28).
- **Areas where a high number of hot spots tend to happen recurrently (M8)**: is represented by the hotspot mark in the map.

Finally, an intensive work has been performed in relation to the verification and validation of the proposed framework and developed tools. Details have been reported in deliverable R.2 (public access).

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[2] AsloEarth is used here, but analogous visualisation is expected from R-NEST

Figure 21. Envelope layer. Example of two envelopes intersecting at a time instant.

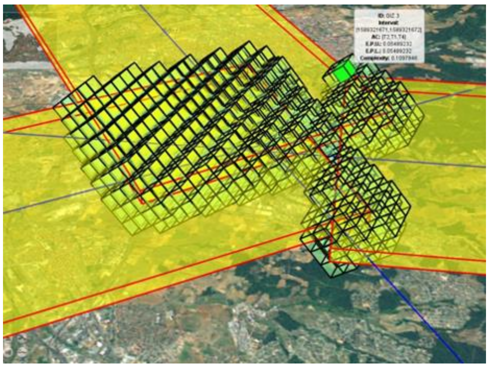

Figure 22. G_IZ Instant layer showing a voxelated intersection

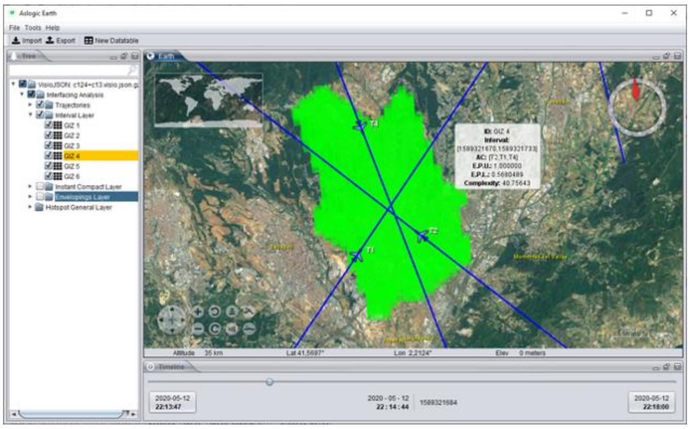

Figure 23. The G_IZ layer. Showing a G_IZ between three trajectories.

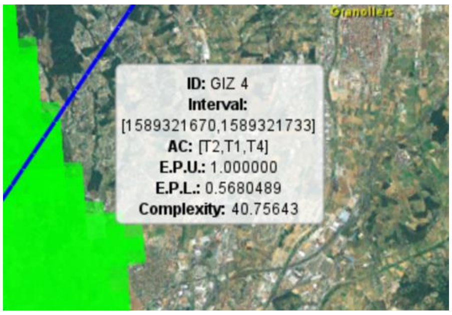

Figure 24. Detail of the G_IZ info box.

Figure 25. Hotspot layer. Hotspots are represented using an aircraft icon and the interdependency as a blue line.

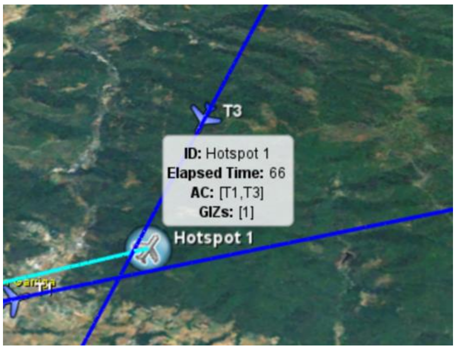

Figure 26. Detail of the Hotspot info box.

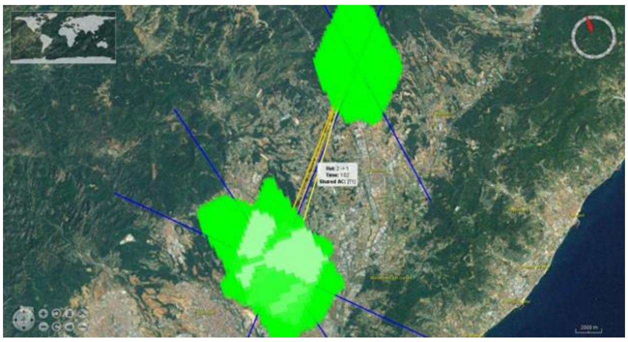

Figure 27. Interdependencies between two G_IZs (yellow lines)

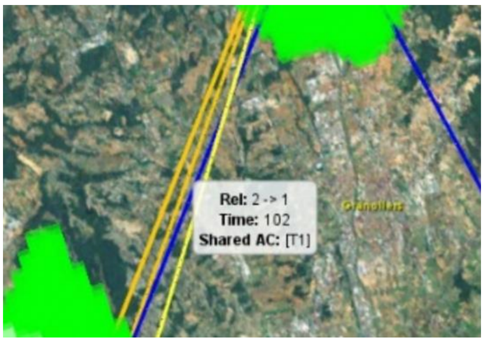

Figure 28. Detail of a Hotspot interdependence info box

3. Conclusions, next steps and lessons learned

3.1 Conclusions

Overall, the project objectives have been successfully achieved providing a satisfactory answer to the formulated research questions. On the view of the achieved results, the formal probabilistic framework and the interdependency analysis provide a set of metrics that quantify and visualize relevant in-depth information about the foreseen evolution of the Interaction Zones, anticipates the impact of the involved flights on the ATC activity, as well as their up and down-stream interdependencies. Therefore, the project has successfully addressed the two (expected positive) impacts for ATM:

- Enhancement of the DCB for the sake of ATC Minimum Intervention. INTERFACING metrics and the interdependency causal analysis complement and enrich traditional indicators, such as entry and occupancy count and traffic complexity, that participate in the capacity analysis. The Interaction Zones can be framed at sector level, providing a deeper insight on the possible conflicting situation ATC will face. It could be expected that the consolidation of the implemented metrics opens the opportunity to investigate on new mitigation measures through the ATFCM phases, ranging from the LTM to the EAP lookahead with respect to ATC timeframe.
- Improve transparency and efficiency of DCB network services. The new metrics and spatiotemporal interdependencies provide an insight into the Interaction Zones at trajectory level, so the mitigation measures to remove the interactions can be implemented at trajectory level instead of at sector level. Therefore, an efficiency improvement could be expected since constraints (e.g. a sector regulation) can be transformed into decision variables (e.g. which is the minimum set of flights that should be regulated to reduce the complexity of a given Interaction Zone or Hotspot). Transparency would benefit from the causal analysis at trajectory level since the need to implement certain mitigation measures can be explained from the up & downstream negative effects a given flight or set of flights are causing.

Table 3 summarises the main contributions to the TC2 topics that have been addressed by the project, according to the feedback received from EUROCONTROL and also during the performed project presentation (e.g. SIDs December'19).

Table 3. main contributions to Thematic Challenge 2

Scope of the Thematic Challenge 2 topics	Topic addressed in INTERFACING
Development of tools for the identification of 'hotspots' and the evaluation of different ATFCM measures	INTERFACING has extended the PARTAKE functionalities to digitalize the full European ATM. The Interaction Zones and Hotspots have been formalised and the algorithms to detect them have been implemented and verified. New interaction metrics to characterise the Interaction Zones and Hotspots have been proposed and implemented. Furthermore, as set of algorithms performing the causal analysis for identifying the interaction zones and its spatio-temporal dynamics have been also implemented and verified.
Bridging the gaps between the temporal phases of ATFCM	The micro-level analysis of spatio-temporal interdependencies among trajectories aims at providing interaction metrics in a time frame ranging from the LTM (6 – 1h) and the INAP/EAP (40 – 10 minutes) lookahead with respect to ATC timeframe. We expect the proposed probabilistic analysis at trajectory level to contribute to Network planning enhancement, paving

	the way for new mitigation measures, prior to the ATC tactical phase, that could be based on the confidence that this probabilistic approach provides.
Optimising and integrating local planning activities with a view to assess, contain and communicate their network effects	The causal analysis tools, adapted from in PARTAKE and extended to the proposed probabilistic formalisation of Interaction Zones, provide an anticipatory functionality to evaluate the impact of un-coordinated local constraints. As a first step, an INTERFACING specific version has been implemented for its integration within R-NEST. We expect the ATM community and the ongoing research dealing with the scalability effects at network level can benefit from the outcomes of this project.
Improving data-sharing and data access to satisfy AU, NM and ANSP technical and organizational requirements and expectations.	INTERFACING metrics and interdependency analysis provide a deep understanding and explainability of the upstream and downstream negative effects of regulations applied to the wrong time and sectors. We expect from the new interaction-zone metrics, as well as the causal analysis of their interdependencies, to become a baseline to predict at Network level the effects from traffic regulations at trajectory level, paving the way for new DCB tools to enhance the propagation of positive effects by applying the right regulations at the right time window for the right latent interaction-zones.

3.2 Next steps

Two actions are already scheduled by September'20. The first one will be the presentation of the developed tools in EUROCONTROL. Apart from exploring new opportunities to move forward the project results, we expect from this meeting to assess the opportunities for demonstrating the tools in an ACC. The second activity will be the presentation in the next Engage Summer School, where we expect to raise awareness and interest of results among the ATM community and engage the Industry attending the event in supporting the project way forward. Also, we expect to present the project results and findings in the next Engage KTN workshop.

So far, the algorithms yield sound results according to the implemented V&V strategy. Nevertheless, we expect from these actions to open opportunities for further validation activities. The fine tuning of the algorithm parameters deserves further research to assess the confidence on the algorithms for computing Interaction Zone existence and metrics. Big data analysis is envisaged as a promising approach for validation activities, using past traffic data along with the airspace configuration and the regulations potentially applied. Simulation and scenario analysis of ATM planning activities (e.g. using R-NEST) is also envisaged as a way forward to raise interest on the produced tools and outcomes.

Additionally, we foresee the following application areas that, in our opinion, deserve further research to develop the project even further:

1. *Analysis and assessment activities*. INTERFACING algorithms operate at trajectory level, to take benefit of the TBO concept and also of the most advanced avionic enablers (EPP, what-if EPP). Furthermore, the algorithms are highly scalable, both in time and in space. With respect to time, the algorithm parameter setup can be tuned to cover the various ATFCM phases, from early assessment using the RBT with a high level of uncertainty to the LTM and INAP/EAP phases, with an increasing level of accuracy in the trajectory predictability. As to space, the current prototype release running in a standard laptop can analyse in few minutes up to 2 hours of European traffic in a peak period. So, it has proved its capabilities to operate at NM level down to FIR, CTA and even Sector levels. A non-exhaustive list of envisaged applications follows:

   a. Assess the performance of interaction management ant Network level. For example, to determine the performance impact at the Network level of the implementation of CASA and STAM measures. We expect from the integration with R-NEST to easily complement the global indicators evaluation (e.g. capacity, route length extension, ATFCM/Non-ATFCM delays, etc.) with the impact of the implemented measures on the Interaction Zones.
   b. Enrich Network Performance Indicators. INTERFACING can complement traditional performance indicators used at strategic planning, predicting the Interaction Zone metrics across Europe using a trajectory driven approach and providing a meaningful visualisation of the complex results to the ATM stakeholders.
   c. Learn from data. The combination of Big Data (based on past traffic) and A.I. based learning methods, opens opportunities to identify, for instance, correlations between Interactions Zones and certain traffic flow patterns, or particular airspace configurations or applied ATFCM measures (e.g. regulations). This learning capabilities could drive the research in new decision-making strategies to resolve interactions.
   d. Supporting tools to ATCO for mid and short-term conflict detection. Using the most updated trajectory data (e.g. available at the FDPS) and the right parameter setup for handling the uncertainty in this time horizon (e.g. impact of some particular weather conditions), the Interaction Zone analysis could be used for detecting potential conflicts including its probability to occur.
   e. *Sectorless* ATM concept. The capability to predict in which Interaction Zones a given flight will be involved and also which other flights are participating can support the design of procedures for assigning flights to controllers (Flight-centred ATC) and also to anticipate the controllers that will be involved in the resolution of the predicted interactions.
2. *Automated tools for supporting decision making*. INTERFACING interaction metrics are measuring the level of spatio-temporal dependencies between aircraft trajectories (micro level), by taking into account potential deviations of aircraft along its trajectory, that is, by considering uncertainty. Furthermore, the developed formalisation of the Interactions Zones and their interdependencies, provides the opportunity to design new mitigation measures that could be surgically implemented at trajectory level. A non-exhaustive list of envisaged applications follows:
   a. Trajectory-based DCB measures at the ATM network level. The INTERFACING hotspot metrics identify the flights that are linking different Interaction Zones (interdependencies), opening the opportunity to investigate on trajectory-based DBC measures to minimize future interactions and also to reduce the interdependencies that can propagate negative effects.
   b. Empower the Integrated Network Management and the Extended ATC Planning function. INAP/EAP aims at providing protection filters to deliver the controller a traffic situation compatible with his mental resources. The *G_IZ*, as a characterisation of the spatio-temporal interactions among two or more aircrafts, brings an opportunity to investigate on new resolution mechanisms in a time frame LTM/EAP where nowadays a gap exists.
   c. Conflict Resolution support. The INTERFACING Interaction Zone characterisation applied in the ATC phase enables mechanisms for better identification of a conflict likelihood. Furthermore, the spatio-temporal characterisation of a potential conflict opens the opportunity to design resolution measures considering the surrounding traffic to avoid induced conflicts.

3.3 Lessons learned

- First mention is to the Engage KTN programme. In our case, this action has provided us a very suitable and "open-mind" framework for promoting some initial results into a new state, taking advantage of the feedback received from prior research, as well as during the project, in order to mature the concepts. Its light administrative burden is also considered very positively, as well as the always supportive coordination team.

- The early definition of the evaluation strategy and the concept of operations helped a lot the development phase, not just because of having a clear path to follow, but also because of many of the computational challenges could be anticipated that, to a certain extent, guided some relevant design decisions.
- During the definition of evaluation strategy, it has been very beneficial to validate the requirements and take a discussion time with EUROCONTROL to assess the concept of operation. Somehow, the evaluation strategy provides a view of the end-user interests (i.e. ATM community).
- It is a time-consuming task to get traffic data from DDR2, due to the download pace limitations (it takes several weeks to get traffic for one AIRAC cycle). Nevertheless, we appreciate to have had DDR2 access during the project lifecycle.
- Finally, few words about the COVID-19 lockdown impact. It has been mostly the cause for most of the project delay, although an optimistic effort estimation during the preparation of the proposal is partly to blame. Furthermore, some of the initially foreseen validation activities have been postponed for autumn. Fortunately, technology has helped to overcome most of the lockdown effects. However, we miss the fruitful group discussions in front of the traditional blackboard (MS Paint is a poor substitute) and also the lunch break.

4. References

4.1 Project outputs

The project has produced the following reports and deliverables:

- The ConOps document where the formal framework and algorithms are described. This is an internal document that has been share with the EUROCONTROL team supporting the concepts and the project an also with the Engage KTM for project assessment purposes.
- Deliverable *R.1. Requirements and use cases*. Report describing the functional and non-functional requirements, the selected use case(s) and traffic scenarios, and the tool evaluation strategy.
- Deliverable *DEM.1 Demonstration Tool*. The application integrating the developed algorithms and visualisation tools. This is an internal material that, nevertheless, we expect to make it available to the ATM community as a R-NEST plugin.
- Deliverable *R.2: Verification and Validation report* describing the validation methodology used in the software implemented according to prototype testing and feedback, together with the metrics obtained.

As to project presentations worthy to mention:

- The discussions and engagement achieved from EUROCONTROL, as ATM stakeholder, have enabled Aslogic to set the basis for a concept and to materialize in a tangible toolkit a concept that is targeting objectives aligned with current ATM challenges, in spite the concept is still close to the research level.
- The meeting we had with a representative of the ISOBAR project, awarded in the recent SESAR ER4 Call. INTERFACING concept and tools were presented, and it has been considered their potential use in the WP where an algorithm with "reinforcement learning" will be developed to automate/facilitate Flow Management Position tasks. It could also be used to train an automatic ATCO.

4.2 Other

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Annexes

A.1 Glossary of terms

In most cases, the definitions of EUROCONTROL were used because they are widely used by the ATM community and are always used in the same way for operational purposes. In some cases, definitions were adopted towards the INTERFACING context.

Term	*Definition*
Complexity (intrinsic)	In the INTERFACING context, it measures the intrinsic structure of the G_IZ, i.e., how many pairwise interactions contain and how they interact among them. This metric provides a value greater or equal to zero, the greater this value is, the more complex a G_IZ is. As an aggregated indicator, it complements the existing traffic characteristic complexity indicators.
Concurrence Event (Potential)	In the INTERFACING context, a potential conflict among two or more A/C occurs when they are predicted to have a spatiotemporal relationship below a given time and distance thresholds.
Conflict	Event in which a loss of separation minima occurs.
Hotspot	In the INTERFACING context, a hotspot is an aggregation of Interaction Zones sharing at least one A/C and happening in time intervals separated below a given threshold.
Interaction Zone	An Interaction Zone (*IZ*) is an airspace region in which during a time interval there is the possibility (not null probability) that two or more A/C to co-exist.
Macro level analysis	In the INTERFACING context, macro level is meant to the analysis of the interdependencies among interaction zones (either distributed through different sectors or spatially concentrated in the same sector) to enable a proper understanding of the spatiotemporal interdependencies.
Micro level analysis	In the INTERFACING context, micro level is meant to the 4D trajectory analysis performed to detect and characterise the Interaction Zones.
Predictability	A measure of delay and/or position variance from the current A/C position until the successive planned waypoint.
Sensitivity	Sensitivity refers to the capability of a system to react/respond to a given input. In the particular case of PARTAKE, sensitivity could refer to the capability to perform a change in a given Key Performance Area.
Spatiotemporal relationship	Spatial and temporal relationship among two or more A/C of interest for a given purpose. For instance, identifying a potential loss of separation.
Uncertainty	Uncertainty is a situation caused by unknown information concerning a vertical, cross-track or along-track deviation with respect to the planned trajectory.
Unfeasible trajectory	In the context of the probabilistic formulation, it is a trajectory which can't be flown by an aircraft (e.g. disconnected in time, with sudden and abrupt changes in heading or altitude, etc)

A.2 Acronyms

Term	*Definition*
A/C - AC	Aircraft
ACC	Air-Traffic Control Centre
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATFCM	Air Traffic Flow and Capacity Management
CASA	Computer Assisted Slot Allocation
ConOps	Concept of Operations
DST	Decision Support Tool
EPP	Extended Projected Profile
FL	Flight Level
G_IZ	Generalized Interaction Zone
IZ	Interaction Zone
LTM	Local Traffic Management
NM	Nautical Mile
NM	Network Manager
PARTAKE	cooPerative depArtuRes for a compeTitive ATM networK sErvice
pdf	Probability density function
P_IZ	Pairwise Interaction Zone
RBT	Reference Business Trajectory
SBT	Shared Business Trajectory
SESAR	Single European Sky ATM Research
SM	Separation Management
SOA	Service-based Architectures
STAM	Short-Term ATFCM Measures
SWIM	System Wide Information Management
TBO	Trajectory Based Operations
WP	Work Package