Self-Reorganized Supporting Tools for Conflict Resolution in High-Density Airspace Volumes

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Abstract — Present research on Air Traffic Management (ATM) is tending to improve airspace capacity, accessibility and the efficiency of operations in high-density areas, while maintaining or improving the safety performance indicators. Tactical interventions from the Air Traffic Control (ATC) system to preserve safety distances between aircraft have some inherent drawbacks when scalability problems arise, that could lead to a well-known capacity saturation. An increased number of detected conflicts in dense traffic volumes can affect not only the ATC procedures but also the full safety net, since the present Traffic Alert and Collision Avoidance System (TCAS) has been designed only for low dense areas. To overcome these shortages at tactical level without appealing to the strategic airspace restrictions, this paper presents an innovative automation-based concept in future design of the ATM system supporting an irruptive shift from the centrally controlled ATM system to a distributed system, in which a set of aircraft constitutes a dynamic ecosystem, with self-governed capabilities, to find the optimal conflict-free resolution trajectories. The concept has been developed within the methodological approach “hotspot-cluster-ecosystem” which provides a smooth transition from trajectory management (TM), separation management (SM) to the collision avoidance (CA) layer, seeking for an advanced time horizon in which the airspace users would timely negotiate resolutions before an ATC directive is issued. A dynamic demand-capacity balance (DCB) approach is illustrated by identifying clusters and analyzing ecosystems considering deviations of pairwise conflicting aircraft to the surrounding traffic (ST). The ecosystem is described by its membership size and spatially temporal interdependencies (STIs), i.e. potential 4D positions of the members driven by defined maneuverability checks, and generated conflict intervals between each pair of members. Finally, computed interdependencies provide an insight of the ecosystem complexity through the ratio of a total number of feasible resolutions over the ecosystem time.

Keywords - component; conflict detection; clustering; ecosystem; traffic extraction; deadlock; spatially-temporal interdependencies.

I. INTRODUCTION

The constant increase in the air transport demand leads to the emergence of some hotspot airspace volumes during certain time windows that generates a continuous pressure on the SM layer. Consequently, more efforts in the ATC modernization have been made to satisfy the main ATM criteria: enhanced capacity, efficiency and safety. Based on the SESAR (Single European Sky ATM Research) and NextGen (Next Generation Air Transportation System) initiatives [1], [2], it is expected to move from the completely centralized tactical ATC interventions to the highly decentralized operations relying on advanced decision support tools (DSTs). This predicts an important change in the roles, situational awareness, tool functionalities and responsibilities of the overall ATM system.

At operational level, an upgraded TCAS II v.7.1, has been designed for operations in the traffic densities of 0.3 aircraft per squared nautical mile. The system demonstrates an excellent performance in cases of the pairwise encounters but, unfortunately, shows some operational drawbacks in its logic due to well reported induced collisions in certain traffic scenarios [3], [4], [5]. The current operational drawbacks emerge also due to a lack of integration between SM at the tactical level, and CA at the operational level.

To address these safety drawbacks in present and future air traffic, the AGENT (“Adaptive self-Governed aerial Ecosystem by Negotiated Traffic”) project [6] claims for a collaborative and proactive SM system considering a socio-technological approach, in which both human behavior and automation will play an important role. AGENT, as one of the SESAR H2020 Exploratory Research projects, envisages an operational integration of seamless safety procedures in such a way that aircraft involved in a pair-wise encounter, together with the aircraft in the surrounding airspace behave as a stable conflict free “ecosystem”. The project defines the new operational framework though development of both the airborne and ground-based DSTs that will generate the trajectory amendments for the ecosystem members taking the spatial-temporal interdependencies between aircraft into consideration. The AGENT DSTs will work in line with the current and future SESAR requirements to provide a robust SM system considering aircraft performances and the scalability problem to support different traffic complexity levels [7], [8].
To achieve the full operational compatibility, it will be necessary for validation purposes to detect and map all the conflicts within extracted traffic, and increase volume densities by introducing synthetic 4D trajectories during certain time intervals. Thus, the STIs between aircraft are analyzed through a four-step identification process:

- **Traffic extraction**: Input data usually provide traffic in 24 hours of operations and the goal is to extract number of 4D trajectories in a highly dense airspace volume by filtering them above certain FL (in AGENT operational environment is considered above FL245), and then within selected time interval (for instance, 2 hours of traffic);

- **Intent-based conflict detection (CD)**: The algorithm only considers the pairwise encounters and over-takings. It considers intents of two approaching aircraft returning a value that indicates a predicted loss of standard separation minima (SSM) between them. Prediction is also characterized by an advanced time interval, namely look-ahead time (LAT), continuously projected along trajectories;

- **Cluster creation**: A set of extracted trajectories filtered both in time and space around a single detected conflict. The cluster volume is defined by projected points at the LAT instants, and computed safety buffers added to these points. The cluster members are considered as aircraft flying inside this volume by identification of their 4D stamps;

- **Ecosystem creation**: Cluster trajectories with potential STIs between the cluster members in which any of two conflicting aircraft making a potential maneuver would force direct or indirect trajectory amendment of another cluster aircraft. With respect to SSM, the ecosystem members are determined by the time stamp overlaps.

The key issue in the resolution of an ecosystem is to identify the time limit above which an induced collision could emerge due to a conflict avoidance maneuver. This time limit is called ecosystem deadlock event (EDE) and depends on the geometric profiles of the ecosystem trajectories, aircraft closure rates and performance. EDE is computed and triggered by the ATC and characterized by the time instant at which at least one ecosystem member cannot perform any feasible maneuver leading to the conflict-free solution. Instead, an induced collision could emerge. The time frame between the ecosystem creation and the EDE instant is used by the ecosystem members to negotiate their conflict resolutions (CR). This negotiation is implemented by means of the agent technology in which each aircraft is enhanced by an agent that follows the airline business model used to identify preferred amended trajectories. This technology provides the right framework to support the negotiation between the ecosystem members to reach a CR consensus avoiding the ATC intervention which does not consider the airline preferences. Fig.1 depicts the AGENT communication and negotiation framework. Therefore, the goal is to calculate the conflict interval for each member during the ecosystem time. This time is defined as an advanced time, i.e. look-ahead time (LAT), in which the ATC predicts a conflict occurrence between two aircraft in encounter. In AGENT, LAT starts 300 seconds before the Closest Point of Approach (CPA), and is timely positioned between two ATC thresholds: Mid-Term Conflict Detection (MTCD) − 15 minutes, and Short-Term Conflict Alert (STCA) − 120 seconds.

![Ecosystem identification](image)

This paper illustrates the ecosystem creation procedure from the traffic extraction to the ecosystem membership identification in a simulated environment. It briefly describes the intent-based CD algorithm, summarizes the traffic extraction procedure and illustrates the process to identify the ecosystem interdependencies which are used to compute EDE. The remainder of the paper is organized as follows. Section II discusses the background on the collision events and motivation for the time horizon extension. Section III elaborates the transitional process in methodological way, while Section IV provides test evidence and preliminary results. Section V completes the content with conclusions.

## II. BACKGROUND

This section describes the reasons and effects for introduction of the AGENT operational framework.

### A. TCAS logic for pair-wise encounters

TCAS computes a time to the Closest Point of Approach (CPA) between two conflicting aircraft as a ratio between the range and closure rate, or range rate. The CPA is an estimated point at which the distance between two aircraft in encounter will reach its minimal value. Both range and range rate in horizontal plane are obtained from the TCAS interrogations, usually with one-second update, and they apply to aircraft in cruising configuration. In vertical plane, the time to co-altitude (vertical tau) is computed as a vertical separation divided by a vertical closure rate [8]. TCAS issues two types of alerts: Traffic Advisories (TAs), helping pilots in a visual search for traffic aircraft and to prepare them for a potential maneuver amendment, and Resolution Advisories (RAs), that recommend maneuvers leading to either increase or maintenance of existing vertical separation from an intruder aircraft.

There are three common rules in the logic of TCAS for pair-wise encounters described in Fig. 2 [9]:

![Ecosystem communication](image)
i. two RAs are opposite to each other, they advise an opposite sense for maneuvers to the crew. For instance, climb-descend or descend-climb is defined as reversal TCAS logic.

ii. when RAs are issued, the aircraft at a lower altitude performs descending maneuver and the one at higher altitude climbing, without considering the current flight configuration: cruise, climb or descent;

iii. two aircraft after the RA activation must achieve a minimum vertical separation at the CPA called Altitude Limitation (ALIM), measured in feet (ft).

An induced pair-wise encounter lies in fact that, after successfully resolved conflicts, a new conflict event with surrounding traffic around the CPA cannot be easily predicted. Instead, surrounding traffic introduces a certain level of uncertainty in geometry of a pair-wise resolution trajectories and, thus, very tight STIs between trajectories, that could degenerate into collision, are essential for definition of the conflict region itself. Even if assumed that flight parameters, such as heading and closure rates are progressively maintained, which also imply the constant time stamp updates, it is not possible to predict an induced CPA by an analytical computational model.

Naturally, this question opens many analytical aspects, but the main ones are a limited TCAS logic based on the specific number of RAs, TCAS threshold requirements, and the feasible manoeuvres based on aircraft performances [10]. TABLE I gives the TCAS thresholds for different altitude ranges.

<table>
<thead>
<tr>
<th>Own Altitude (feet)</th>
<th>SL</th>
<th>TAU (seconds)</th>
<th>DMOD (nmi)</th>
<th>ZTHR (feet)</th>
<th>ALIM (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 - 2350</td>
<td>3</td>
<td>15</td>
<td>0.33</td>
<td>850</td>
<td>600</td>
</tr>
<tr>
<td>2350 - 5000</td>
<td>4</td>
<td>20</td>
<td>0.48</td>
<td>850</td>
<td>600</td>
</tr>
<tr>
<td>5000 - 10000</td>
<td>5</td>
<td>25</td>
<td>0.75</td>
<td>850</td>
<td>600</td>
</tr>
<tr>
<td>10000 - 20000</td>
<td>6</td>
<td>30</td>
<td>1.00</td>
<td>850</td>
<td>600</td>
</tr>
<tr>
<td>20000 - 42000</td>
<td>7</td>
<td>35</td>
<td>1.30</td>
<td>850</td>
<td>700</td>
</tr>
<tr>
<td>&gt; 42000</td>
<td>7</td>
<td>35</td>
<td>1.30</td>
<td>1200</td>
<td>800</td>
</tr>
</tbody>
</table>

B. Time horizon problem

To explain the concept of induced collision let us first consider an initial state of a non-vectored traffic scenario [11]. There are four aircraft A/C01, A/C02, A/C03 and A/C04 flying on trajectories that form two predicted encounters A/C01-A/C02 and A/C03-A/C04 (Fig. 3). A/C01 is cruising on FL160 while A/C02 starts descending at FL180 in the opposite direction from A/C01, which assumes a direct approach to A/C01 with a loss of height. On the other hand, A/C03 starts climbing at FL130 and approaching to A/C04, which is cruising at FL153 in opposite direction from A/C01.

As it can be seen, both conflicts are successfully resolved after activation of the Traffic Advisories (TA), at the time stamps of the four aircraft, respectively, and then followed by the corresponding RAs, at the time stamps.
The required minimal vertical and horizontal distances, ALIM and DMOD, have been successfully achieved at both CPAs. As a collision avoidance layer (TABLE I) activates in less than 60 seconds and RA’s are issued in less than 35 seconds before the CPA reachability, once resolved conflicts produce very high uncertainty in guidance over amended Reference Business Trajectories (RBTs). After their amendments, A/C01 and A/C04 generated a new conflict and were automatically alerted by the succeeding RAs, at time stamps $t_{RA1}$ and $t_{RA2}$ respectively. Unfortunately, due to insufficient time for the appropriate maneuvers the aircraft came into induced collision.

TCAS is operating in vertical plane which could consider a set of vertical RAs only. Therefore, a collision event is predominantly affected by the downstream traffic flows.

### III. METHODOLOGY

#### A. Intent-based conflict detection

The CD presents a potential spatial convergence between two aircraft that results in a loss of the standard separation minima, which is 5 NM horizontally and 1000 ft vertically. It is a result of the state-based estimation of the aircraft dynamics, STIs between two aircraft as well as an inherited environment. However, the CD process itself is quite complex and requires a multi-layer definition. Fig. 4 illustrates a CD procedure.

As it can be seen, it is a five-level process that starts with a state-based aircraft estimation. It is performed by a given position and velocity. The output is the dynamic state expressing also the flight configuration (cruise, climb or descent). This is propagated to the next level that should determine the aircraft intent. Inputs, such as flight plan, weather, navigation aids or restricted zones helps to predict the aircraft intent. For instance, weather conditions can limit aircraft to follow RBT in any of its segments and, therefore, temporally change/ amend it by flying to another waypoint (WP). From the inferred intent, a subsequent WP is estimated. This WP is projected to the next stage from which the trajectory is predicted. The prediction considers some uncertainties or variations that affect the aircraft dynamic state [12]. For instance, if an aircraft levelling-off at specific altitude presents an additional intent information between two WPs, the more accurate trajectory could be predicted. However, this information might be still unreliable as a pilot may level-off or descend though intended altitude. The succeeding computation is characterized by a probability density function and generated output is the probabilistic trajectory [13]. The final stage is defined by a probabilistic conflict prediction that computes the conflict probability.

The process considers the pair-wise CDs only, that are the main generator for the cluster creation [14], and the ecosystem identification. Implemented tool relies on the Stratway [15], strategic conflict detection method.

#### B. Hotspot-cluster transition at tactical level

Since AGENT validation is performed in a simulated environment, the full traffic in a selected day of operations over the European en-route airspace is extracted. Time filtering is done with respect to the selected interval duration (for instance, 2 hours) and a time of day (i.e. morning, or afternoon). Proposed methodology is structured in 4 steps:

1. Clustering of all traffic around detected conflicts. The method is based on computation of the spatial limits for a pair of 3D points bounding the conflict interval, by adding safety buffers to their coordinates: latitude, longitude and altitude.
2. Extended clustering is an additional procedure supporting clustering that is targeted to identification of additional traffic that may affect the cluster members;
3. Ecosystem membership identification through causal analysis of STIs.
4. Worst Case Scenario (WCS) generation considers amendments of any extended cluster trajectories to increase the ecosystem membership size.

Initial filtering can be done either in time or space. RBTs give a possibility for a 4D data extraction in given region over the full operational day. However, since one of the goals of this research is dynamic traffic density analysis [16], the time filtering is performed. The hotspot is treated as a time-based category comprising many pairwise conflicts that will be analysed for the clusters identification. Fig. 5 illustrates the full traffic day in European airspace, while Fig. 6 represents filtered
en-route traffic in 2 hours. A cloud of points on Fig. 7 depicts all detected conflicts within one airspace sector of the filtered traffic.

Cluster is formed in the following way. For each conflict, it is recorded the conflict time and the 3D coordinates (latitude, longitude, altitude) of two involved aircraft at the CPA. Given that $t_{conflict}$ is the conflict time, $\varphi_{min}$ is the minimal latitude at which one of the two conflict aircraft flies during the time interval $[h_{conflict} - 300, t_{conflict}]$, $\lambda_{min}$ is the minimal longitude, and $h_{min}$ is the minimal altitude. The maximum values, namely $\varphi_{max}$, $\lambda_{max}$ and $h_{max}$ are defined analogously. The surrounding traffic aircraft within cluster is treated in the simulated framework as aircraft whose RBT during the time $[t_{conflict} - 300, t_{conflict}]$ includes 4D point(s), such that:

a. their latitudes are inside the range $[\varphi_{min} - 10\,\text{NM}, \varphi_{max} + 10\,\text{NM}]$;

b. their longitudes are inside the range $[\lambda_{min} - 10\,\text{NM}, \lambda_{max} + 10\,\text{NM}]$;

c. their altitudes are inside the range $[h_{min} - 2000\,\text{ft}, h_{max} + 2000\,\text{ft}]$;

The cluster identification algorithm is therefore implemented throughout seven subtasks:

1. Linear interpolation of the conflict trajectories by projecting the LAT interval in reverse, i.e. $t_{conflict} - 300$. Performed computation outputs the time stamps as the LAT instants;

2. Computing 3D coordinates at the LAT instant for both trajectories and obtain 4D LAT points (LATPs);

3. Extracting the following 4D points from the flight envelopes: LATP_1, CPA_1, LATP_2, CPA_2;

4. Perform minimization and maximization function by identifying $\varphi_{min}$, $\varphi_{max}$, $\lambda_{min}$, $\lambda_{max}$, $h_{min}$ and $h_{max}$;

5. Construct the cluster coordinates (box-shaped volume) by adding or subtracting the values from Step 4 by cluster safety distances (buffers):

$$
\begin{align*}
\varphi_b &= \varphi_{min} - 10\,\text{NM} \\
\varphi_u &= \varphi_{max} + 10\,\text{NM} \\
\lambda_b &= \lambda_{min} - 10\,\text{NM} \\
\lambda_u &= \lambda_{max} + 10\,\text{NM} \\
h_b &= h_{min} - 2000\,\text{ft} \\
h_u &= h_{max} + 2000\,\text{ft}
\end{align*}
$$

(1)

6. Performing re-filtering of extracted data between the following ranges:

- $\varphi_b - \varphi_u$ (latitude column);
- $\lambda_b - \lambda_u$ (longitude column);
- $h_b - h_u$ (altitude column).

7. Identify all 4D points inside the cluster volume and match them with the corresponding flight IDs. These IDs present the cluster members.

Fig. 8 and Fig. 9 illustrate the cluster projection in horizontal and vertical plane, respectively. Red points present 4D conflict points for the pair-wise encounter, while the blue ones denote the corresponding 4D trajectory points shifted 300
seconds back. Points in other colors inside this volume match the surrounding trajectories by re-filtering procedure.

This analysis best matches the high-speed enroute environment with very frequent over-takings, in which extended cluster members can easily diverge within 300 seconds into the ecosystem members and generate the worst case scenarios. The extended clustering algorithm is fully compliant with described CD approach, and implemented through the following three subtasks:

1. Extending the cluster volume by computing new set of coordinates, i.e. adding/subtracting the safety distances to/from the minimal values (LATP coordinates):
   \[ \varphi_{\text{b}}' = \varphi_{\text{min}} - 15 \text{NM} \]
   \[ \varphi_{\text{u}}' = \varphi_{\text{max}} + 15 \text{NM} \]
   \[ \lambda_{\text{b}}' = \lambda_{\text{min}} - 15 \text{NM} \]
   \[ \lambda_{\text{u}}' = \lambda_{\text{max}} + 15 \text{NM} \]
   \[ h_{\text{b}}' = h_{\text{min}} - 3000 \text{ft} \]
   \[ h_{\text{u}}' = h_{\text{max}} + 3000 \text{ft} \]

2. Performing re-filtering between the following ranges:
   - \( \varphi_{\text{b}}' - \varphi_{\text{u}}' \) (latitude column);
   - \( \lambda_{\text{b}}' - \lambda_{\text{u}}' \) (longitude column);
   - \( h_{\text{b}}' - h_{\text{u}}' \) (altitude column).

3. Identifying all 4D points inside the extended cluster volume and matching them with the corresponding flight IDs. These IDs present surrounding traffic potentially evolving into the cluster if they deviate from their RBTs.

**D. Worst case scenario**

There are many factors that could affect the trajectory deviations with respect to the RBT. However, the goal of the supporting tools in evaluation of the AGENT performances for collision avoidance mechanisms is not to validate deviation models, but rather to derive the ecosystem complexity from the trajectory degenerations [17], in terms of the number of members and evolving geometries. Evaluation of the WCS complexity may serve for validation of the AGENT tools, as well as measuring the performance metrics within an integrated simulation platform (exploitation of the solutions).

Based on the scenario in Fig. 10, Fig. 11 shows a case in which extended cluster evolves into the WCS because of the trajectory amendments in previous surrounding conflicts.
E. Ecosystem identification

The ecosystem identification algorithm determines all cluster members as surrounding traffic for which the loss of SSM with any of the conflict aircraft could occur if this aircraft would perform a given maneuver during the ecosystem time. The criterion for the ecosystem formation is the conflict time overlap between the initial conflicting aircraft and surrounding aircraft within the cluster. Considerably, the ecosystem membership is a spatially-temporal category. Maneuverability is defined in both horizontal and vertical plane (Fig. 12). It is based on the triangle-based algorithm, assuming the aircraft position and speed vector estimation in case of the time stamp overlaps for the ray-triangle intersection [18]. There are four possible avoidance manoeuvres currently considered in AGENT:

- L: Left heading with an angle of 15 degrees;
- R: Right heading with an angle of 15 degrees;
- C: Climb with a vertical rate of 500 ft/min;
- D: Descent with a vertical rate of 500 ft/min.

![Figure 12. Triangle-based profile in (a) horizontal plane, (b) vertical plane](image)

It is conventionally agreed that the ecosystem member searching for a conflict-free resolution can amend its RBT only in 2D space, meaning to perform either a heading maneuver or a vertical speed change.

IV. TESTS AND PRELIMINARY RESULTS

This section describes the data used for hotspot-cluster-ecosystem processing and compares two ecosystem scenarios.

The main source of data for validation purposes in AGENT presents Demand Data Repository 2 (DDR2) [19], developed and maintained by EUROCONTROL. DDR2 is a comprehensive database intended for both the airspace users and ATC for carrying out different studies and analysis in ATM. It contains a variety of traffic data, such as historical, filtered and forecast traffic, as well the analytical tools and reporting sections. The scenarios are generated using historical data, exclusively by taking the planned 4D trajectories (RBTs) in the so-called s06 model 1 (m1) data format [20].

The main hotspot elements obtained from the simulation runs are: number of extracted trajectories, total number of conflicts and total number of clusters. Then, the statistics on the clustering structure is provided, given the classification of the specific number of clusters and extended clusters per number of the members. For instance, 7 cluster – 3 members, 3 clusters – 4 members, etc. The following data have been used for testing:

- Historical traffic dated on 12/01/2017, with s06.m1 data model;
- Total number of RBTs: 24570;
- Traffic extraction set to 2h (120’), in the selected period 08.00 - 10.00;
- Clustering has been performed for different minimum FLs, i.e. from FL200 to FL350;

The analysis did not consider the conflicts that occur out of the conflict intervals due to the aircraft intent effects on trajectory prediction. TABLE II, TABLE III and TABLE IV output the following results:

<table>
<thead>
<tr>
<th>FL</th>
<th>Hotspot: 12/01/2017_m1, 08.00 - 10.00 (120’)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of flights</td>
</tr>
<tr>
<td>200</td>
<td>2555</td>
</tr>
<tr>
<td>210</td>
<td>2509</td>
</tr>
<tr>
<td>220</td>
<td>2351</td>
</tr>
<tr>
<td>230</td>
<td>2409</td>
</tr>
<tr>
<td>240</td>
<td>2323</td>
</tr>
<tr>
<td>250</td>
<td>2244</td>
</tr>
<tr>
<td>260</td>
<td>2185</td>
</tr>
<tr>
<td>270</td>
<td>2158</td>
</tr>
<tr>
<td>280</td>
<td>2096</td>
</tr>
<tr>
<td>290</td>
<td>2019</td>
</tr>
<tr>
<td>300</td>
<td>1963</td>
</tr>
<tr>
<td>310</td>
<td>1905</td>
</tr>
<tr>
<td>320</td>
<td>1842</td>
</tr>
<tr>
<td>330</td>
<td>1789</td>
</tr>
<tr>
<td>340</td>
<td>1722</td>
</tr>
<tr>
<td>350</td>
<td>1693</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of members per cluster</th>
<th>Number of clusters</th>
<th>Number of extended clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
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<td>6</td>
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<td>7</td>
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<tr>
<td>8</td>
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<td>9</td>
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<td>1</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
The simulations are performed at different FLs for getting a better insight of the conflict dynamics. Logically, from FL200 there must be cumulatively more flights and detected conflicts as the monitored airspace is larger. As already stated, AGENT is placed above FL245, but the clustering structure is compared between FL200 and FL350 to find a trend of the conflict occurrences for the merged traffic to the minimal altitude layer. Fig. 13 illustrates cluster – extended cluster transition above FL210 and FL 250, respectively.

![Figure 13: Comparison between cluster – extended cluster transitions above FL200 and FL300](image-url)

It can be noted a higher drop in the number of clusters and extended clusters between 2 and 3 members at both FL200 and FL300. Two clusters have been identified for the WCS. In first case, it is chosen one cluster with 6 members, while the second is a cluster with 4 members. TABLE V and TABLE VI provide information on the ecosystem identification.

### TABLE IV. Cluster structure above FL300

<table>
<thead>
<tr>
<th>Number of members per cluster</th>
<th>Number of clusters</th>
<th>Number of extended clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>4</td>
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<tr>
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<td>3</td>
</tr>
<tr>
<td>6</td>
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<tr>
<td>7</td>
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<tr>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The first part of both tables describes linear segments within the cluster volume providing the starting and ending 4D points, i.e. latitude, longitude, altitude and time. First column in the table is always reserved for the aircraft ID. Second part provides information on the interdependencies between the ecosystem members in terms of the type of maneuverability (left heading L, right heading R, climb C and descent D) and the conflict interval (measured in seconds) for this potential amendment. The conflict interval is a period within the LAT (\(t_{\text{conflict}} – 300\), \(t_{\text{conflict}}\)), computed with the respect to the CPA. Fig. 14 describes both scenarios in 3D Euclidean space.

![4D elements of the ecosystem members](image-url)

![Figure 14: 3D Euclidean space representation](image-url)
For both scenarios, all cluster members evolve into ecosystem members, since at least one maneuver applied to each member generates the conflict interval (in rectangular brackets) with another member(s). An empty cell means that a given aircraft can perform the conflict-free maneuver. For instance, in case of Scenario I, if A/C3 performs descent, it will be in conflict both with A/C1, during the interval [33969, 34107] seconds, and A/C2, during the interval [33969, 34090] seconds. The plots on Fig. 15 describe the spatial profiles in time of the trajectories in Scenario I, identifying STIs over different conflict intervals. The profiles are projected as per RBT segments.

Obtained results demonstrate that Scenario I have higher perishable speed than Scenario II. This is reflected in the number of members, but also due to trajectory geometries. Agents in Scenario I should reach consensus during the first 30 seconds since an amount of the feasible resolutions drops drastically, reaching EDE 122 seconds after triggering the ecosystem. On the other hand, the elapsed time in negotiation for Scenario II is more flexible as the number of resolutions decreases with lower trend until the first 100 seconds, reaching EDE 135 seconds after triggering the ecosystem.

V. CONCLUSION

To satisfy the main objective of this research, that concerns the aircraft ecosystem complexity levels, an appropriate methodology and modeling procedure have been developed for different traffic scenarios. The step-wise algorithm has defined the cluster, extended cluster and ecosystem members taking the spatially-temporal criteria into consideration. The algorithm is intended to work with both real and synthetic traffic, providing a smooth transition from
trajectory management, separation management to the collision avoidance layer.

Qualitative analysis has shown very good tool performances in the preliminary phase, especially in case of the clustering detection for two hours of operations. A stochastic approach has been used and, therefore, the same traffic scenario can be analyzed in different runs generating different results in each execution. This approach enhances also a mechanism for generation of probabilities to the performance metrics, that can be achieved by the tool.

Described methodology to compute EDE enhances the use of agent technologies as dynamic demand-capacity balance to solve conflicts at tactical level by identifying and tracking the ecosystem trajectories in which the airline business models and preferences can be used to reach a resolution agreement before an ATC compulsory advisory is issued.

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