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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 coming from the Air Traffic Control (ATC) system to preserve safety distances between aircraft have some inherent shortages when scalability problems arise, that could lead to well-known capacity saturation. 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 strategic ATFM 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 aircraft creates dynamic ecosystems, with self-governed capabilities, to find the optimal conflict-free resolutions with respect to the safety and cost-efficiency criteria. The concept has been developed within the methodological approach “hotspot-cluster-ecosystem” which provides a smooth transition from trajectory management, separation management to the collision avoidance layer, seeking for a conflict collision detection time horizon in which AU’s can negotiate a resolution before an ATC directive is issued. The dynamic DCB approach proposed is illustrated by identifying clusters and analyzing ecosystems considering deviations in the surrounding traffic (ST) of a detected pair-wise conflict. The ecosystem is described by its member identifications and spatially temporal interdependencies, i.e. relative positions for the specific metrics with respect to the minimum separation criteria, and conflict intervals of each member. Finally, computed interdependencies provide an insight of the ecosystem complexity through the ratio of a total number of feasible resolutions over the ecosystem time interval.**

Keywords - component; conflict detection; hotspot; clustering; ecosystem members; dynamic demand-capacity balance; 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 separation management (SM) system. As a result, more efforts in the ATC modernization have been made in order to satisfy the main ATM criteria: enhanced capacity, efficiency and safety. Based on the SESAR (Single European Sky ATM Research) NextGen (Next Generation Air Transportation System) initiatives [1], [2] it is expected to move from the completely centralized tactical ATC interventions to a more efficient separation management decentralized tactical operations relying on advanced decision support tools. This predicts an important change in the roles, situational awareness, tool functionalities and responsibilities of the overall ATM system.

At operational level, an upgraded Traffic Alert and Collision Avoidance System (TCAS) II v.7.2, has been designed for operations in the traffic densities of 0.3 aircraft per nautical mile. It 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 some surrounding traffic scenarios [3], [4], [5]. Present operational TCAS drawbacks emerge also due to lack of integration between separation management at tactical level with collision avoidance at operational level.

To address these safety-net 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 decentralized separation management system considering a socio-technological approach in which both human behavior and automation will play an important role. AGENT, as one of the SESAR [5] 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 decision support tools (DSTs) that will generate the trajectory amendments for the ecosystem members taking into account the spatial-temporal interdependencies between aircrafts. The AGENT DSTs will work in line with the current and future SESAR requirements to provide a robust collision avoidance system considering aircraft performance and the scalability problem to support different complexity levels of traffic scenarios.

In order to achieve ta full operational compatibility with present safety regulations, it has been necessary for validation purposes to detect and map all the conflicts in reported traffic (DDR's), increasing volume densities by introducing synthetic RBT's during certain time intervals. As a result, all the spatial and temporal interdependencies between aircraft in pairwise conflict with the surrounding traffic is analyzed through a three-fold filtering process:

- Hotspot – Trajectories in a high density airspace volume;
- Cluster – Hotspot trajectories filtered both in time and 3D space around a single conflict detected; the cluster members are defined as aircraft flying inside this volume;
- Ecosystem – Cluster trajectories with particular interdependencies between the cluster members in which any of two conflicting aircraft making a potential trajectory amendment could force the direct or indirect amendment of another cluster member trajectory. The ecosystem members are determined by the time stamps overlap, with respect to the standard separation minima.

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 collision avoidance maneuver. This time limit is called "Ecosystem Deadlock Event" (EDE) and depends on the particular characteristics of each ecosystem surrounding traffic, aircraft performance and safety regulations. The EDE is computed and triggered by the ATC DST and characterized by the time instant at which all ecosystem members cannot perform any feasible maneuvers leading to the conflict-free solutions. Instead, an induced collision could emerge. The time frame between the ecosystem formation until the EDE is used by the ecosystem members to negotiate a conflict resolution. This negotiation is implemented by means of agent technology in which each aircraft is enhanced by an agent with the business model of the company that is used to identify AU preferred amended trajectories. AGENT technology provides the right framework to support the negotiation between the ecosystem aircraft to reach a CR consensus avoiding the ATC intervention which do not consider AU resolution 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.

Figure 1. Communication process among the ecosystem aircraft

This paper illustrates the AGENT transitional procedure from the hotspot conflict detection (CD) to the ecosystem membership identification in a simulation environment. It briefly describes the intent-based CD algorithm, summarizes the filtering procedure and illustrates the process to identify the ecosystem interdependencies which are used to compute the "Ecosystem Deadlock Event". 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

There are three common rules in the logic of TCAS for pair-wise encounters [7]:

i. two Resolution Advisories (RAs) are opposite to each other, i.e. they advise an opposite sense for maneuver to the crew (for instance, "climb-descend" or "descend-climb"); it is defined as "reversal" TCAS logic, illustrtated in Fig. 1;

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 (cruising, climbing or descent);

iii. two aircraft after RAs activation form two spatial criteria: horizontal separation minima, called DMOD (Distance MODification, measured in nautical miles), and vertical separation minima, called ALIM (Altitude LIMitation, measured in feets), at the CPA. The third requirement is time separation, denoted with "tau" (measured in seconds) which is a contol factor for different Sensitivity Level (SL) index [8]. This one-digit number features a strength sense of a TCAS command. Tau shows remaining time to reaching the CPA and measures an uncertainty level of the trajectory dynamics.

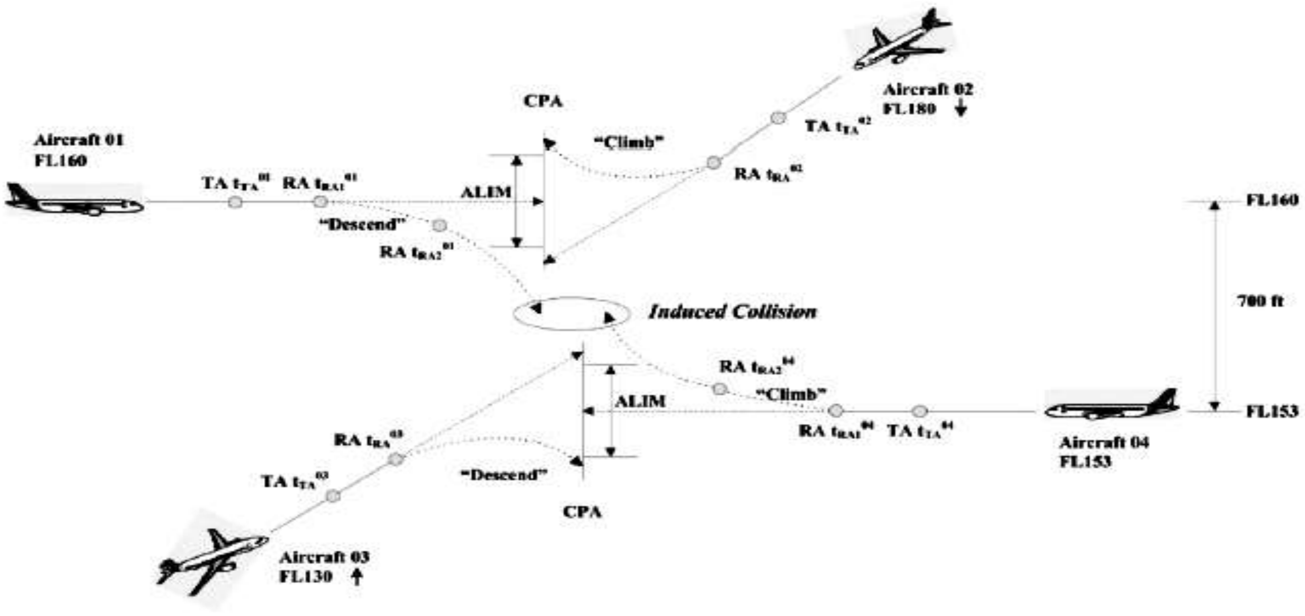


Figure 2. Induced collision scenario

An induced pair-wise encounter event lies in fact that, after successfully resolved conflicts, a ″new″ conflict in the CPA surrounding traffic cannot be easily predicted. Instead, surrounding traffic introduces a certain level of uncertainty in geometry of a pair-wise resolution trajectory and, thus, very tight spatio-temporal interdependencies between trajectories that could degenerate into collision are essential to be identified in order to define the conflict region itself. Even if assumed that flight parameters, such as heading and closure rate, 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 definitely a limited TCAS logic based on the specific number of RAs, TCAS threshold requirements, and the feasible manoeuvers based on aircraft performances [6]. TABLE I gives the TCAS threshold values for different altitude ranges.

TABLE I. TCAS THRESHOLD VALUES

Own Altitude (feet)	SL	TAU (seconds)		DMOD (nmi)		ZTHR (feet)		ALIM (feet)
		TA	*RA*	*TA*	*RA*	*TA*	*RA*	*RA*
1000 - 2350	3	25	15	0.33	0.20	850	600	300
2350 - 5000	4	30	20	0.48	0.35	850	600	300
5000 - 10000	5	40	25	0.75	0.55	850	600	350
10000 - 20000	6	45	30	1.00	0.80	850	600	400
20000 - 42000	7	48	35	1.30	1.10	850	700	600
> 42000	7	48	35	1.30	1.10	1200	800	700

B. Time horizon problem

To explain the concept of induced collision let us first consider an initial state of a non-vectored traffic scenario [9]. 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. 2). A/C01 is cruising on FL160 while A/C02 starts descending at FL180 in the opposite direction from A/C01, which assumes a direct approch to A/C01 with a loss of height. On the other side, A/C03 starts climbing at FL130, and, with its increase in height, approaching to A/C04, which is crusing 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 t_{TA}^{01}, t_{TA}^{02}, t_{TA}^{03} and t_{TA}^{04}, respectively, and then followed by the corresponding RAs, at the time stamps t_{RA1}^{01}, t_{RA}^{02}, t_{RA}^{03} and t_{RA1}^{04}. The required minimal vertical and horizontal distances, ALIM and DMOD, have been successfully achieved at both CPAs. As a collision avoidance layer (Table 1) 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 are automatically alerted by the succeeding RAs, at time stamps t_{RA2}^{01} and t_{RA2}^{04}, respectively. Unfortunately, due to insufficient time for the appropriate maneuvers the aircraft came into induced collision. It is worth mentioning that TCAS is still operating in vertical plane, i.e. a vertical set of RAs with the frequent changes of heading. 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, spatially temporal interdependencies (STI) between the aircraft as well as an inherited environment. However, the CD process itself is quite complex and requires a multi-layer definition. Fig. 3 illustrates a probabilistic conflict detection.

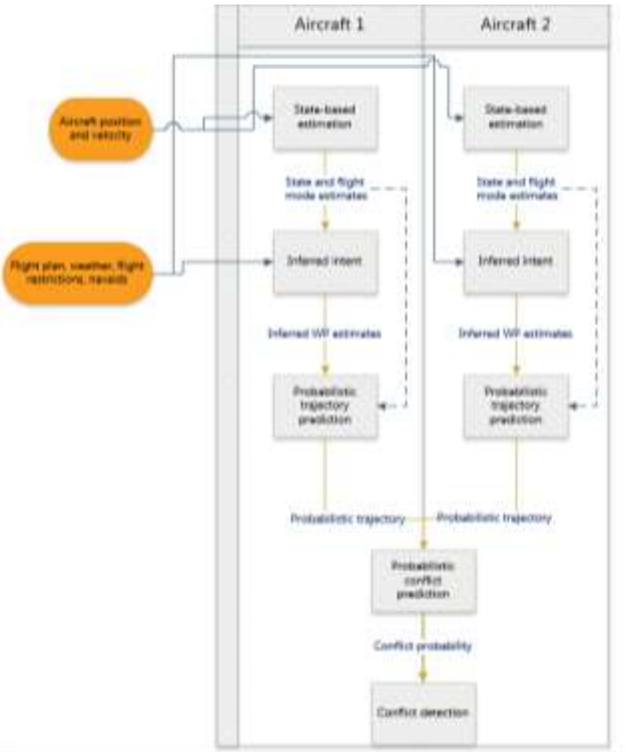


Figure 3. Probabilistic conflict detection process

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. The computation is characterized by a probability density function. The generated output is the probabilistic trajectory. 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 detection and ecosystem identification. The implemented tool relies on the Stratway [10], strategic conflict detection method.

B. Hotspot-cluster transition at tactical level

Since AGENT validation is performed in a simulation environment, an initial filtering of a 24-hours traffic in a selected day of operations over the European en-route airspace is performed. Timely filtering is done with respect to the selected interval duration (2 hours, 1 hour) and a time of day (morning, afternoon). The proposed methodology is composed of 4 steps:

1. Clustering of all traffic around conflicts detected; 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 my affect the cluster members;
3. Ecosystem membership identification through causal analysis of the spatial-temporal interdependencies.
4. Worst Case Scenario (WCS) generation considers amendments of any extended cluster trajectories to increase the ecosystem memberships.

Initial filtering can be done either in time or space. RBTs give a possibility for a 4D data extraction in a given region over the full operational day. However, since one of the goals of this research is the air traffic density analysis, the time filtering is performed. The hotspot is treated as a time-base category comprising many conflicts which will be analysed to identify clusters. Fig. 4 illustrates the full traffic day in European airspace. The yellow cells denote the higher traffic density areas of operations while the green ones are with lower density.

Figure 4. Traffic flow using 24 hours of operations in Europe

Fig. 5 presents 2 hours filtered traffic, while Fig. 6 shows re-filtered traffic in 1 hour.

Figure 5. Traffic flow using 2-hour time filter in Europe

Figure 6. Traffic flow using 1-hour time filter in Europe

The cloud of points in Fig. 5 and Fig. 6 denotes clusters. The spatial-temporal bounded cluster of aircraft provides the main information required by the AGENT probabilistic tool to identify the nominal scenarios in which the ecosystem members should reach a set of conflict resolutions agreed during a negotiation process before the "Ecosystem Deadlock Event" in which an ATC intervention will be issued. Thus, the evolution of a cluster towards an ecosystem relies mainly on the detection of a conflict between two or more aircraft. In early stages of AGENT, only pair-wise conflicts will be considered for the clusters generation, but the AGENT framework has been designed to consider multithread conflicts as well.

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, lat_{min} is the minimal latitude at which one of the two conflict aircraft flies during the time interval [$t_{conflict}$ – LAT, $t_{conflict}$], lon_{min} is the minimal longitude, and alt_{min} is the minimal altitude. lat_{max}, lon_{max} and alt_{max} are defined analogously. The surrounding traffic aircraft within cluster is treated in the simulation 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 [lat_{min} – 10NM, lat_{max} + 10NM];
b. their longitudes are inside the range [lon_{min} – 10NM, lon_{max} + 10NM];
c. their altitudes are inside the range [alt_{min} – 10NM, alt_{max} + 10NM];

The cluster identification algorithm is therefore implemented through six subtasks:

1. Linear interpolation of the conflict trajectories by projecting 300 seconds interval in reverse, i.e. $t_{conflict}$ – 300. Performed computation outputs the time stamps as the LAT instants;
2. Compute 3D coordinates at LAT instant for both trajectories and obtain 4D LAT points (LATP);
3. Extract the following 4D points from the flight envelopes: $LATP_1$, CPA_1, $LATP_2$, CPA_2;
4. Perform minimization and maximization function by identifying lat_{min}, lat_{max}, lon_{min}, lon_{max}, alt_{min} and alt_{max};
5. Construct the cluster volume (box-shaped) by computing the offset lines and then intersecting them:

$$\begin{aligned} L_1 &= lat_{min} - 10\text{ NM}, \\ L_2 &= lat_{max} + 10\text{ NM}, \\ L_3 &= lon_{min} - 10\text{ NM}, \\ L_4 &= lon_{max} + 10\text{ NM}, \\ L_5 &= alt_{min} - 2000\text{ ft}, \\ L_6 &= alt_{max} + 2000\text{ ft}. \end{aligned} \tag{1}$$

6. Perform filtering of the input data between the following ranges:
   - $L_1 - L_2$ (''Latitude'' column),
   - $L_3 - L_4$ (''Longitude'' column),
   - $L_5 - L_6$ (''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. Computed airspace provides very good approximation for the ecosystem detection.

Fig. 7 and Fig. 8 illustrate the cluster projection in horizontal and vertical plane, respectively. Red points present 4D conflict points for the pair-wise encounter, while the green ones present the corresponding 4D trajectory points shifted 300 seconds back. Points in other colors inside this volume match the surrounding trajectories by re-filtering procedure.

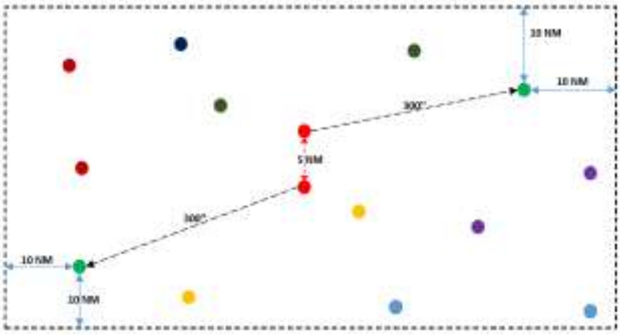


Figure 7. Cluster projection in horizontal plane

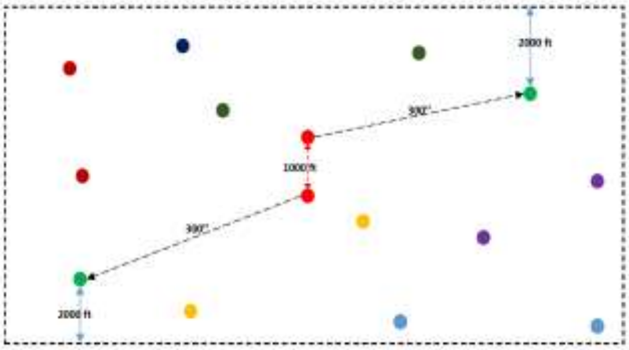


Figure 8. Cluster projection in vertical plane

C. *Extended clustering*

For the purpose of the Worst Case Scenario generation, the algorithm extends the cluster for each identified ecosystem. This extended volume of a given conflict is defined as the set of aircraft containing:

- The aircraft involved in the conflict;
- The aircraft from nearby conflicts, i.e. conflicts that occur in a radius of 15 NM in latitude and longitude, 3000 ft in altitude and no more 300 seconds before the occurrence of the given conflict.

In Fig. 9, the concept of extended cluster is presented for a scenario that could be achieved by random generation of the realistic trajectory deviations for potential conflicts inside the extended cluster, in a way that surrounding traffic can evolve into the ecosystem.

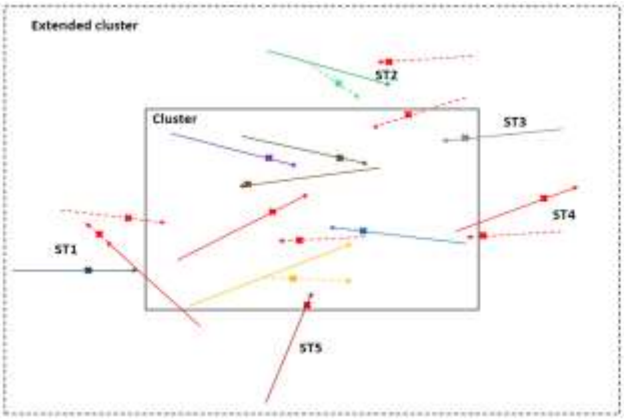


Figure 9. Surrounding traffic estimation through extended cluster – cluster transition

This analysis best matches the high-speed enroute environment with very frequent „catch-ups“, 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 also relying on the conflict detection approach, implemented through next three subtasks:

1. Extend the cluster volume by computing new set of the offset lines and then intersect them, i.e.:

$$\begin{aligned} L_1' &= lat_{min} - 15\text{ NM}, \\ L_2' &= lat_{max} + 15\text{ NM}, \\ L_3' &= lon_{min} - 15\text{ NM}, \\ L_4' &= lon_{max} + 15\text{ NM}, \\ L_5' &= alt_{min} - 3000\text{ ft}, \\ L_6' &= alt_{max} + 3000\text{ ft}. \end{aligned} \tag{2}$$

2. Extract the cluster members (flight IDs) from the input data and perform the filtering between the following ranges:
   - $L_1' - L_2'$ (''Latitude'' column),
   - $L_3' - L_4'$ (''Longitude'' column),
   - $L_5' - L_6'$ (''Altitude'' column).
3. Identify all 4D points inside the extended cluster volume and match them with the corresponding flight IDs. These IDs present surrounding traffic potentially evolving into the cluster if they deviate from their original 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 to evaluate the AGENT performance of collision avoidance ecosystem mechanisms is not to validate deviation models, but rather to derive the ecosystem complexity from the trajectory degenerations, in terms of the number of members and evolving geometries. Evaluation of ecosystem complexity fed with the WCS and the key performance indicators (KPIs) obtained from the ecosystem resolution process will serve for:

- Validation of the AGENT tools for complex scenarios;
- Measure the performance metrics of AGENT tools within one simulation platform, Open Demonstrator (OD);
- Learning from the AGENT shortcomings and improve the ecosystem negotiation process.

Fig. 10 demonstrates the case in which extended cluster evolves into the WCS as a consequence of the ST deviations.

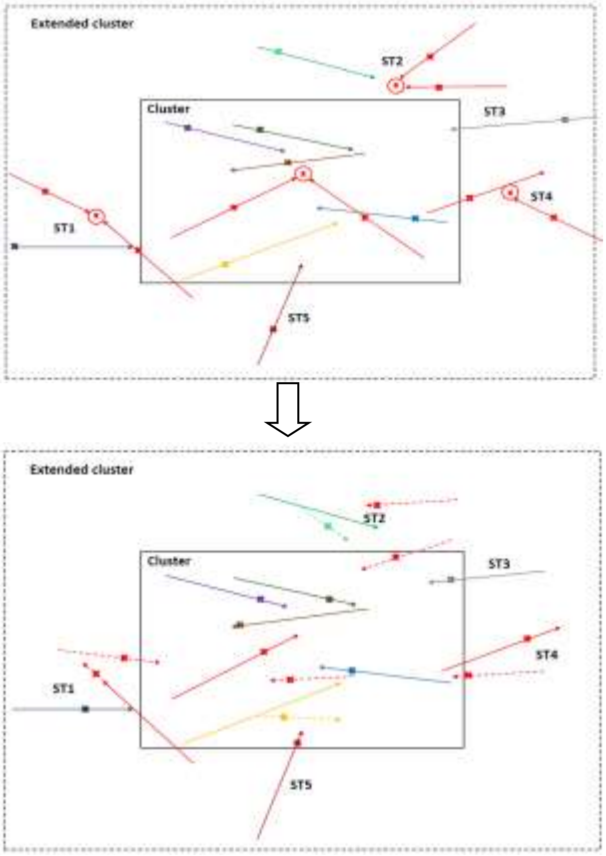


Figure 10. Extended cluster - WCS transition

E. Ecosystem Identification

In terms of the membership size, AGENT classifies three ecosystem types:

1. Simple, 2 members (aircraft in conflict only);
2. Nominal, 3 - 4 members;
3. Complex, 5 or more members.

The ecosystem identification algorithm determines all cluster members as surrounding traffic for which the loss of separation with any of the conflict aircraft would occur if this aircraft performs a given manoeuver at its LATP. The criterion for the ecosystem formation is the conflict time overlaps between the maneuvering conflict aircraft and the surrounding aircraft within the cluster. Considerably, the ecosystem membership is a temporal category. Maneuverability is defined in both horizontal and vertical plane (Fig. 10). 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 [11]. There are four possible avoidance manoeuvers considered in AGENT:

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

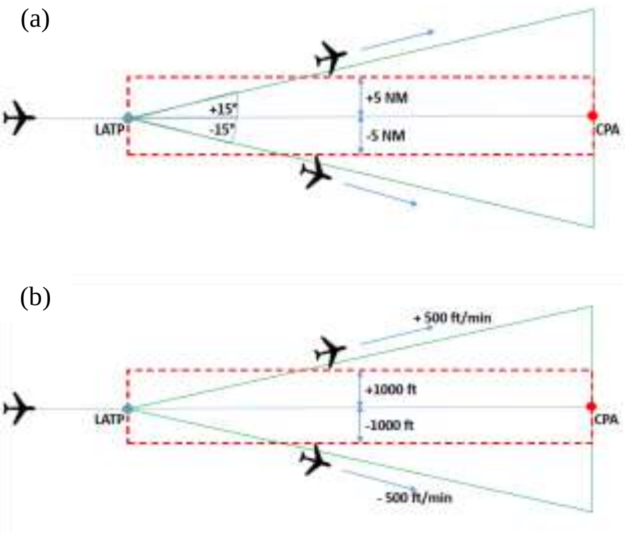


Figure 11. Tringle-based profile in (a) horizontal plane, (b) vertical plane

In AGENT, it is conventionally agreed that the ecosystem member searching for a conflict-free resolution can amend its RBT only in 2D, meaning that it is possible to perform either heading or vertical rate change.

IV. TESTS AND PRELIMINARY RESULTS

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

The main source of data for validation purposes in AGENT is Demand Data Repository 2 (DDR2) [12], 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 the planned 4D trajectories (RBTs) in the so-called *s06 model 1* (m1) data format.

The main hotspot elements obtained from the simulation runs are: number of extracted trajectories, total number of conflicts and total number of clusters. Total number of extended clusters is not considered as it must be equal to the total number of clusters. Then, the statistics on the clustering structure is provided, given the classification of the specific number of clusters per number of its members. For instance, 7 cluster – 3 members, 3 clusters – 4 members, etc.

The following data have been used for testing:

- Historical traffic dated on 16/01/2017, with s06.m1 data model;
- Total number of RBTs – 26225;
- Initial filtering has been set to 2h (120'), in the selected period 17.00:19.00.
- Clustering has been performed for different minimal FLs, i.e. from FL210 to FL300;

The analysis has not considered catch-up conflicts as well as 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 II. HOTSPOT STRUCTURE

FL	**Hotspot: 16/01/2017_m1, 17.00:19.00 (120')**		
	Number of flights	***Number of conflicts***	***Number of clusters***
210	2509	84	20
220	2451	80	19
230	2409	80	18
240	2324	72	18
250	2244	74	17
260	2185	72	18
270	2158	69	16
280	2096	65	15
290	2019	71	17
300	1963	66	17

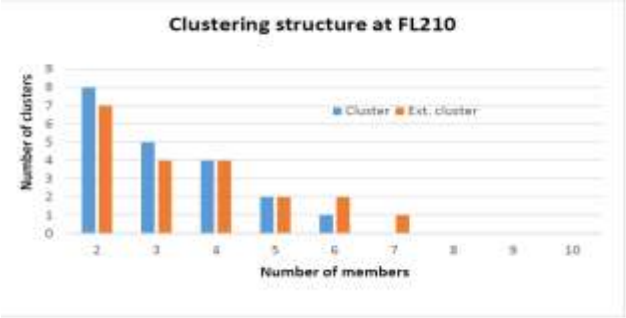
TABLE III. CLUSTER STRUCTURE AT FL210

Number of members per cluster	**Cluster and extended cluster structure at FL210**	
	Number of clusters	***Number of extended clusters***
2	8	7
3	5	4
4	4	4
5	2	2
6	1	2
7	0	1
8	0	0
9	0	0
10	0	0

TABLE IV. CLUSTER STRUCTURE AT FL250

Number of members per cluster	**Cluster and extended cluster structure at FL250**	
	Number of clusters	***Number of extended clusters***
2	9	6
3	5	5
4	2	3
5	0	1
6	1	1
7	0	1
8	0	0
9	0	0
10	0	0

The simulations are performed at different FLs in order to get better insight of the conflict dynamics. Logically, from FL210 there will be more flights and, consequently, conflicts as the available airspace is larger. As already stated, AGENT is placed above FL245, but the clustering structure is compared between FL210 and FL250 in order to find a trend of the conflict occurrences for the emergent traffic to the AGENT layer. Fig. 12 illustrates cluster – extended cluster transition at FL210 and FL 250.



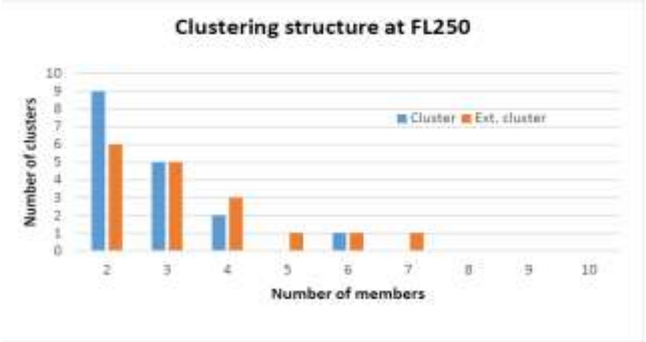


Figure 12. Trend in cluster – extended cluster transition

It can be noted a higher drop in the number of clusters consisting of 2 and 3 members at FL250, while the same applies to both the clusters and extended clusters at FL210. Two extended clusters have been identified for the WCS. In first case, it is chosen one extended cluster with 6 members at FL210 while the second is an extended cluster with 4 members at FL250. TABLE V and TABLE VI provides information on the ecosystem identification and spatially-temporal interdependencies among the members.

TABLE V. SCENARIO I AT FL210

A/C	**4D elements of the ecosystem members**							
	LAT1	***LON1***	***ALT1***	***T1***	***LAT2***	***LON2***	***ALT2***	***T2***
1	44.785	12.554	22000	3130	44.560	13.054	21700	3430
2	44.751	13.045	21250	3162	44.745	13.014	21600	3462
3	44.668	12.453	22800	3000	44.669	12.920	22350	3300
4	44.884	13.304	21500	2950	44.881	13.115	21500	3250
5	44.750	12.721	21800	2975	44.750	13.230	22000	3275
6	44.973	13.420	22200	3060	44.977	12.815	22550	3360

A/C	**Ecosystem interdependencies**			
	L	***R***	***C***	***D***
1	2 [120, 60] 4 [300,120]	2 [260,60] 3 [300,75]	5 [300,90]	2 [300,120]
2	1 [120,60] 3 [300, 60]	1 [260,60]	-	3 [250, 60]
3	1 [300, 75] 2 [300, 60]	4 [300, 210] 5 [300, 100]	-	-
4	5 [300, 160]	2 [260, 60] 3 [300, 75]	5 [300, 90]	3 [300, 120]
5	-	6 [300, 90]	4 [300, 90]	6 [300, 75]
6	5 [300,220]	4 [300, 200]	2 [260, 60] 3 [300, 75]	2 [300, 120]

TABLE VI. SCENARIO II AT FL250

A/C	**4D elements of ecosystem members**							
	LAT1	***LON1***	***ALT1***	***T1***	***LAT2***	***LON2***	***ALT2***	***T2***
1	35.784	22.554	26000	2150	35.780	23.054	25800	2450
2	35.751	23.554	25300	2162	35.753	23.051	25500	2462
3	35.667	22.554	26800	2155	35.676	23.047	26350	2455
4	35.884	23.304	26200	2143	35.848	22.804	26550	2443

A/C	Ecosystem interdependencies			
	L	***R***	***C***	***D***
1	2 [112, 60] 4 [300,112]	2 [263,60] 3 [300,74]	-	2 [300,120]
2	1 [112,60] 3 [300, 60]	1 [263,60]	1 [300,120]	-
3	1 [300, 74] 2 [300, 60]	-	-	-
4	1 [300,112]	-	-	-

The first part of both tables describes linear segments within the cluster volume provided with starting and ending 4D points, i.e. latitude, longitude, altitude and time. First column in the tables 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 (turn Left, turn Right, Climb, Descend) and the conflict interval (measured in seconds) for this action. The conflict interval is a period within the LAT ($t_{conflict}$ – 300, $t_{conflict}$), computed with the respect to the CPA.

For both scenarios, all cluster members evolve into ecosystem members, since at least one maneuver applied to each members generates the conflict interval (in rectangular brackets) with other member(s). Empty cells mean that given aircraft is allowed to perform the conflict-free maneuver. For instance, in case of Scenario I, if A/C 2 performs left heading, it will be in conflict both with A/C1 during the interval 120 – 60 seconds and A/C3 in period 300 – 60 seconds before the CPA. It is very important to emphasize that a minimal threshold for the conflict interval is set to 60 seconds, since the lower values would lead the ecosystem members to the collision avoidance (CA) layer, which belongs to the TCAS region.

Fig. 13 describes the rate of change – speed in the number of the feasible combinations of conflict-free resolutions over the ecosystem time. It can be seen that complex scenario (Scenario I) has a significant drop in first 100 seconds. Naturally, its deadlock state occurs earlier than Scenario II as the number of feasible resolution maneuvers decreases faster in time, due to trajectory geometry constraints.

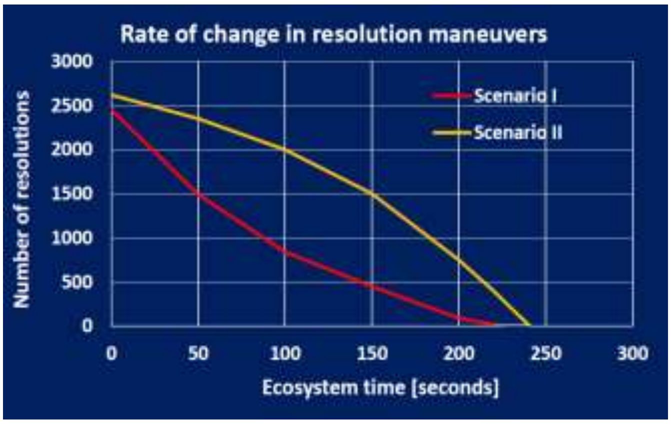


Figure 13. Scenario I – Scenario II ratio in the number of resolutions

Obtained results demonstrate that Scenario I generates more complexity than Scenario II. This is reflected in the number of members but also the trajectory geometries as interdependencies are present for both horizontal and vertical maneuvers. Agents in scenario I should reach a consensus during the first 100 seconds of the ecosystem formation since the amount of feasible resolutions drops drastically reaching the EDE at time 200. On the other side, Scenario II is the nominal ecosystem (4 members) and provides more flexibility in vertical maneuvers providing a better gap for the agent negotiation process.

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 algorithms have defined the cluster, extended cluster and ecosystem volumes taking into account the spatially-temporal criteria. The algorithms are intended to work with both real and synthetic traffic, from the pair-wise conflicts detection 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 AGENT.

Described methodology to compute the ·Ecosystem Deadlock Event” enhances the use of agent technologies as dynamic demand-capacity balance to solve conflicts at tactical level by a self-reorganization of the ecosystem trajectories in which AU’s business models and preferences can be used to reach a resolution agreement before an ATC resolution is issued.

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