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AGENT

ADAPTIVE SELF-GOVERNED AERIAL ECOSYSTEM BY NEGOTIATED TRAFFIC

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Abstract

This document is reporting the final results obtained at the end of AGENT lifecycle. The report is released as the final deliverable, D7.2: Final Project Results Report within the work package WP7: Project Management. AGENT project provides the baseline for a new scalable ATM framework with a smooth transition between the safety net layers, relying on a validated decentralized control system in which airspace users takes an active role in the conflict resolution tasks through a negotiation process supported by agent technology, and the ATC preserves present situational awareness.

Starting with the brief Executive Summary, the document makes the comprehensive overview of the project scope and objectives, operational and technical context, as well as a description of the main work performed in each work package. It elaborates the key results achieved with respect to the AGENT Concept of Operations and list the technical deliverables whose content has contributed to generation of these results.

The report identifies the corresponding links to the SESAR Programme through its contribution to the current ATM Master Plan and maturity assessment taking into consideration the project Technology Readiness Level, different criteria, rationales and satisfaction levels. In addition, the report draws the relevant conclusions and points to the lessons learned during the project lifetime.

Finally, the document lists all the references related to the project deliverables, project publications and other scientific references used for the development of the AGENT tools and the Open Demonstrator.

Table of Contents

List of Tables

List of Figures

1 Executive Summary

This document provides the AGENT Final Project Results, summarizing the qualitative and quantitative performance achieved as a project overview, the links to the SESAR programme, and provides both lessons learned at WP level and an elaborated set of new research areas to be considered as roadmap for the future research to move AGENT framework to higher TRL. The document has been prepared by the AGENT Consortium Members and recap the activities performed in each area of the project.

AGENT framework facilitates the operational integration among Trajectory Management, SeparationManagement and Collision Avoidance activities, for seamless efficient safety procedures, proposing an Adaptive self-Governed aerial Ecosystem by Negotiated Traffic (AGENT) concept. AGENT envisages a flight efficient, safe collaborative and supervised separation management, operationally integrated to trajectory management and collision avoidance layers.

The new framework developed rely on the concept of Aerial Ecosystem to provide a seamless transition between separation management at the tactical level and collision avoidance algorithms at the operational level, by means of a cooperative efficient conflict-free framework. The aerial ecosystems can be understood as a paradigm of the complex adaptive systems, in which aircraft trajectories change and evolve over time because of interactions between the ecosystem members and its ever-changing environment.

At functional level, the aerial ecosystem framework provides an analysis of spatiotemporal interdependencies between aircraft located in the airspace volume, proximate to a detected pairwise conflict that will lead to a trajectory amendment. By checking the manoeuvrability impact of any aircraft that could be affected by a conflict resolution, it is possible to identify a subset of trajectory amendments that will not cause a negative domino effect with the neighbouring aircraft.

For validation purposes, it has been implemented an Open Demonstrator (OD) under a modular approach to allow end-users (both academia and practitioners) to change/improve/replace one of the main services:Cluster Creation (Identification of pairwise conflicts and surrounding traffic), Ecosystem Creation (Identification of all Spatio-Temporal Interdependencies between pairwise aircraft and surrounding traffic aircraft), Conflict Resolution Negotiation Process (Ontology to reach a resolution consensus between ecosystem members supporting hidden AU's business models), Compulsory Resolution (ATC directives to solve the conflict if no consensus is reached).

The quantitative results achieved using the OD confirms that the Aerial Ecosystem framework can tackle the scalability problems of future increment on traffic demand and a more efficient use of the airspace. Furthermore, the qualitative results (face validation with ATM experts) encourage a follow-up research activities in the automation area of the future ATM system.

The maturity assessment is in compliance to the "Introduction to SESAR Maturity Criteria" (edition 1.1.02) and "How to use the Maturity Assessment Tool to Examine SESAR Maturity" (edition1.1.00) and the "Maturity Assessment excel file" as a template.

The Project Management Plan is based on the Grant Agreement, under number: 699313 – AGENT - H2020-SESAR-2015-1/H2020-SESAR-2015-1, provided by the European Commission.

2 Project Overview

2.1 Operational/Technical Context

Nowadays, the separation management (SM) function is generally assigned to the Air Traffic Control (ATC) while flying within the Instrumental Flight Rules (IFRs), and it is applied by ground controllers issuing separation instructions to the crew. This situation applies while the situation is considered as a SM issue and then, involved A/C have more than the TCAS traffic alert (TA) time to reach the closest point of approach (CPA) (less than 1 minute). In near future, an alteration of this responsibility of the ATC is not expected. Figure 1 illustrates the AGENT approach, where TM also involves all those management activities producing operational trajectory changes during the flight, driven by both, efficiency and safety targets. That is to say, when a conflict due any cause is foreseen, a set of feasible trajectory changes is available for each involved A/C. Therefore, SM should be able to deliver efficient trajectory changes for each of them, solving simultaneously the conflict in an efficient manner.

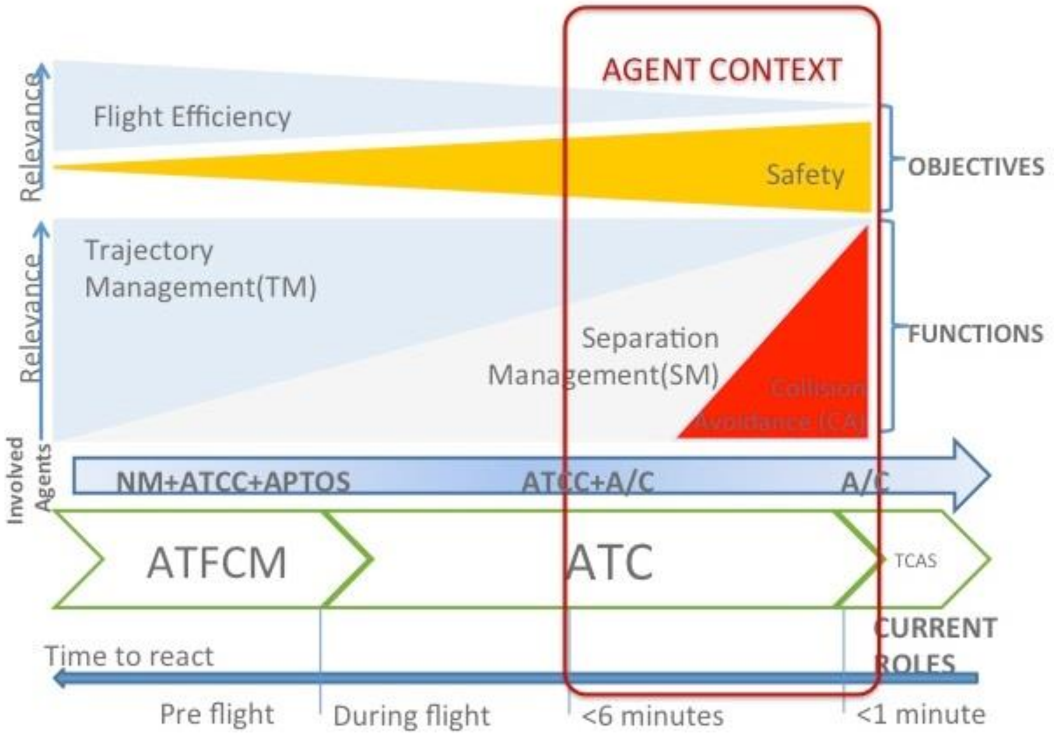

Figure 1: AGENT Context in present Safety net system

Since the evolution of the ATM system still relies on ATCOs for SM tasks, which somehow limits the Airspace capacity. Distribution of SM tasks through different actors can be seen as a solution to present airspace capacity limits. Thus, AGENT is devoted to facilitate the integration between SM and CA activities, questioning the current fixed task allocation on the ground (centric approach), for separation management, and on the air autonomous collision avoidance. To this end, a proactive SM management is proposed supported by multi-agent task allocation, where the "separator's" function will be performed by the ATC, but A/Cs involved in the safety issue (the cluster) will have an active role in the decision-making process, monitored and supported by ground ATC and SWIM.

The project "Adaptive self-Governed aerial Ecosystem by Negotiated Traffic – AGENT" claims for an approach where trajectory management (TM) also involves all those management activities producing operational trajectory changes during the flight, driven by both, efficiency and safety targets. When a conflict due any cause is foreseen, a set of feasible trajectory changes is available for each involved A/C. Therefore, SM should be able to deliver efficient trajectory changes for each of them, solving simultaneously the conflict in an efficient manner.

Regarding integration and continuity of the different safety layers of the system, it is expected to have an improved compatibility between ground and airborne safety nets. In its general scope, AGENT should have been facing during its exploratory lifecycle the following challenges:

- Development of coherent and interoperable ground-based (ATC) and airborne DSTs that will preserve smooth transitions from SM to CA, to find the acceptable and safest resolutions for ecosystem members.
- Generation of negotiation procedures, processes and communication protocols (air-air and air-ground) to support AGENT tools.
- Introducing the metrics for successful safety nets transitions using the most optimal criteria for the Airspace Users.

In addition, the concept assessment introduced new challenges such as:

- Identification of complex and representative scenarios to be solved by AGENT tools.
- Evaluation of the AGENT concept in scenarios representative of the evolution phases of European ATM system.

2.2 Project Scope and Objectives

To support a more efficient ATM system avoiding present problems of fragmented safety net decision support tools, the AGENT project claims for a collaborative, pro-active and socio-technological systems integration in which human behavior plays a significant role. To facilitate the operational integration between the TM, SM and CA safety layers, for seamless efficient safety procedures, the Project proposed the development of the adaptive self-governed aerial ecosystems concept. AGENT envisaged a flight efficient and supervised SM, operationally applied to the Free Route Airspace (FRA) environment.

The Project examines the rate of reduction in the number of feasible, conflict-free avoidance manoeuvres in a tactical air traffic system, relying on the concept of an airborne ecosystem. An ecosystem represents a set of aircraft with the trajectory-amendment and decision-making capability, whose trajectories are identified inside a computed airspace volume, and are causally involved in a safety event. The concept is based on the predicted conflict between two aircraft, whose trajectory segments are used to causally involve the surrounding trajectories by means of the identification of the spatiotemporal interdependencies. AGENT is based on the multi-agent simulation methods for modelling and simulating the negotiation interactions among the aircraft flying over those trajectories and their behaviour in the complex and time-critical system, such as the ATM system.

The core of AGENT foundation lies in development and refinement of decision-making tools to support a cooperative-competitive conflict resolution framework, that can be implemented as ground-based to support ATC's in the generation of compulsory resolutions and also to support FOC's (Flight Operation Centers) for a resolution negotriation that could consider the preferences of the AU's involved in the conflict. It is worthwhile to note, that the negotiation tools could be also implemented in the airside enhancing aircraft as intelligent agents to reach a consensus on the resolution process. These tools in their interoperability, provided by the new algorithms, procedures and operational environment, compose the common simulation framework, the OD. The OD provides the end-users with a comprehensive insight of the traffic safety and efficiency, for any complexity level of a generated scenario: from the pairwise conflict detection to the qualitative and quantitative indicators of the ecosystem resolutions.

Through its active tasks, AGENT has strived to the following objectives:

1. To propose an innovative automation-based design of the ATM system supporting a shift from a centrally controlled ATM system to a distributed system, in which the aircraft and the ATC collaborate for forming the adaptive ecosystems, with self-government capabilities, to find an optimal compromise accounting for safety, capacity and cost-efficiency aspects.
2. To develop ATC Decision Making Tools (DMTs) that would enhance ATC with a set of compulsory resolution trajectories that could be issued at any moment, and a set of tools to monitor the dynamic evolution of the negotiation process between the ecosystem aircraft to determine if a compulsory resolution should be fired.
3. To build the ontology for knowledge representation, reasoning and machine-to-machine communication between intelligent agents, giving rise to a communication vocabulary that enables information sharing with and among the aircraft and ATC (i.e. agents) interacting in the same ecosystem.
4. To verify the DMTs using real traffic data by means of different scenarios in a simulated environment in which traceable and transparent information with provided solutions will be reported.

To demonstrate and quantify the potential for the innovative ATM design to provide benefits in safety, capacity and efficiency of ATM operations, ensuring a wider acceptance of the research results and conducting demonstration activities used to build confidence in the effectiveness of the concept.

2.3 Work Performed

The work performed during the project lifecycle is elaborated through seven Work Packages (WP). Each WP describes the main content developed by the Project Team.

2.3.1 Work Package 1: Scope definition and user needs analysis

The main efforts were put on definition of the Concept of Operations (ConOps) [1], which supports the AGENT operational framework, that rely on the spatio-temporal analysis of the aircraft interdependencies in hotspots, the computation of a set of conflict resolution manoeuvres, and an ontology to support an efficient negotiation mechanism to reach a consensus on the conflict resolution to be flown. The functional and non-functional requirements had been fully explored and elaborated, delimiting the scope of the project, and introducing requirements and assumptions for the scenario to be developed for verification and validation.

Furthermore, the background for the evaluation procedure had been thoroughly analyzed, as well as the metrics developed based on defined procedure. The evaluation was planned as an automatic simulation, as soon as the AGENT framework was implemented, to support a wide range of scenarios and see the behavior of AGENT [2]. The simulations are based on scenarios and possibly some specially developed cases for certain aspects of the system. The quantification and quality of the results had been planned for evaluation by the metrics described.

Finally, the main part of the designing procedure for the OD release had been developed [3]. It comprised definition of the OD functionalities services together with the interoperability requirements, the input and output data structure and data model, as well as the architectural layers, namely user, data and module layers. This structural design should support the multi-level operations and different simulation processes, and support a wide range of the traffic scenarios.

2.3.2 Work Package 2: Design and development of E-TCAS Decision Making Tools

The main efforts in WP2 were dedicated to development of the airborne DMTs. The first developed tool was the multi-objective state space analysis tool (MSSAT) [4]. MSSAT is intended as a multi-objective resolution trajectories algorithm with a step- wise approach. It is divided into two functional blocks: ground-based exploration of the conflict-free airspace and airborne selection of the resolution regions and generation of resolution trajectories. First, the feasible region (FR) for each ecosystem aircraft is been mathematically formalized. This region is further explored for potential sector intersections of two neighboring members with respect to adopted safety metrics – standard separation minima (SSM). The goal was to derive the conflict- free space as a sub-volume of the FR. This space is assigned to each aircraft and, with respect to its RBT geometry, negotiation interval and the airspace users' (AU's) preference, one part of space is selected as a resolution zone. Within this zone each aircraft decides its resolution trajectory (RT) as a set of 4D waypoints (fixes).

The second airborne DMT developed within WP2 was the multi-agent simulation tool (MAST) [5]. The work was oriented towards formalization of the MAST framework, mainly to its structural elements and requirements. The special attention was given to the "satisficing" method for the proposed agents' solutions as a driver of the system acceptability. Moreover, it had been added a set of information that each agent must receive during the ecosystem tracking process. Nevertheless, the system criticality and scalability had been also counted for.

The work task on the OD release has fully covered analysis and generation of the input traffic, i.e. types of trajectories that feed the OD simulation platform, and the characteristics of the scenarios that are generated from the extracted traffic [6]. The main part of the task was the OD data interoperability verification between the module interfaces, focusing on the module inputs and outputs, as well as the parameters for the module execution. The OD platform is composed of four modules:

1. conflict detection;
2. ecosystem identification;
3. compulsory resolution generation;
4. MAS-negotiated resolution generation.

The MAS-negotiated resolution generation is composed of both MSSAT and MAST, whose methods and functionalities complement each other. Finally, to facilitate the future use, the OD GUI has been fully developed through different application features that contain various pieces of information, such as flight information, conflict details, simulation time, ecosystem data, etc.

2.3.3 Work Package 3: Development of ATC smart monitoring and analytics tools

In this WP the workload was oriented towards three toll realises: conflict/collision probabilistic forecasting tool, smart monitoring and analytics tool, and resolution trajectory generation algorithm. These tools covered the main functionalities of three OD modules: conflict detection, ecosystem identification and compulsory resolution generation.

The conflict/collision probabilistic forecasting tool was required to generate scenarios for testing, verification and validation of the AGENT tools, develop probabilistic model and output data generation that will be integrated into the OD [7]. The algorithm itself performs a four-step procedure. First, the input data are timely filtered for a given time interval within an operational day. Then, the conflict detection function is applied for search of all pair-wise conflicts at the tactical level. For this purpose, the standard separation criteria in the en-route traffic are used. Then, the computed safety buffers in distance are used as a for definition of a cluster volume, that presents the third procedural step. In the final step, by applying the spatiotemporal interdependencies as the causal metric, an identification of surrounding traffic aircraft as the ecosystem members is performed.

The smart monitoring ad analytics tool focuses on the dynamic analysis of a decreasing rate in the number of available solutions as well as the ecosystem deadlock event, quantitatively computed from the identified spatiotemporal interdependencies among the ecosystem aircraft [8]. A deadlock event is characterized by a time instant at which an induced collision could emerge as an effect of an ecosystem aircraft trajectory amendment. Through simulations of generated ecosystems, extracted from a real traffic scenarios, the tool has analytically demonstrated an available time capacity for different complexity levels in the resolution process.

The resolution trajectory generation algorithm had addressed the applicable requirements to the development, defined the algorithms, gathered results from simulations, and finally, raised conclusions from the performed exercises [9]. The results from the simulations conducted have shown the expected behavior from the complexity indicator, issuing conflict-free trajectories whereas the complexity of the system was reduced. In addition, it included a delay factor to maintain the efficiency of the system. The algorithm also served as a simulation tool to implement a quantitative approach to identify the time limit of the conflict resolution negotiation proces (also known as the ecosystem deadlock instance), as a complexity measure of the Traffic Alert and Collision Avoidance System (TCAS) time thresholds.

2.3.4 Work Package 4: Ontology development for communication among agents

The work in this WP had provided a basic introduction to the concept of ontology, the types of ontologies and the key aspects to choose the right type of ontology to support the future maintenance and improvement of an agent based conflict resolution application in which AU's interact to reach a consensus in the resolution trajectories to be implemented [10]. Colored Petri Net formalism had been used to describe the agent's interaction during the negotiation process since the interaction of an agent with the rest is both the source of the agent technology power and the source of his problems. To mitigate the interaction problems while enhancing the negotiation capacity of the agents, the proposed ontology provided the baseline to specify the conditions under which an agent request can be satisfied during the negotiation process. In AGENT, the negotiation method ontology was an important objective to support the OD end-users to test different AU's preferences [11].

2.3.5 Work Package 5: Verification and Validation

The main efforts in this WP had covered the verification of the tools implemented within all four OD modules, as well as the validation of the scenarios tested in the OD platform. The modules verification was covering the exploration of the modules methods and functionalities, with respect to the input and output data of each module [12].

The OD architecture is composed of a front- and back-end. The front-end contains a graphical user interface layer whereas the back end contains a data layer and a module layer. Within the module layer AGENT modules are executed. This way AGENT system was constructed based on a module-approach, which enables module-individual verification. Previously established functional and non-functional requirements were mapped to the AGENT modules and tested individually for fulfilling the assigned requirements. As input-data for verification scenarios composed of historic flight plans from DDR2 database by EUROCONTROL have been considered. Regarding the interconnection of AGENT modules, the initial scenarios were fed into appropriate modules for verification and the module output was used as input for verification. Because of changes in AGENT system during development some requirements were rejected or remapped to other modules. Furthermore, the verification was based on some assumptions. This especially included flight plans as the input data and the exclusion of aircraft performance.

Regarding the scenario validation, the validation plan has been introduced by describing the validation process and envisaged validation parameters [13]. Within the validation, the whole system is tested regarding benefits and enhancements. For validation parameters a value for assessing the separation between aircraft have been proposed. Additionally, to this value the track distance and necessary altitude changes for solving conflicts have been used for validating the OD. Validation scenarios are based on historic flight plans from Demand Data Repository 2,owned by EUROCONTROL.

2.3.6 Work Package 6: Dissemination and Exploitation

The tasks in the WP6 have been dedicated to the project communication and dissemination policy and strategy, definition objectives for that, target groups, timeline, metrics, resources and roles, key messages and actions and channels for dissemination [14]. Moreover, some efforts have been made towards development of the project website (http://www.agent-aero.eu/) with all its attributes, in which it can be downloaded all the public deliverables, newsletters, and recent information about follow-up activities [17].

The tasks have also considered the exploitation activities, through definition of the exploitation plan (EP) [15], that had gathered the objectives of the project, the main outcomes (results), to whom the project was directed and what activities should had been developed according to that view. In addition, it established the control mechanisms to ensure that the pursued objectives of the EP are accomplished. There had been also defined the Intellectual Property Rights Management (IPRM) and the actions to be carried out with regard. The initial steps for establishing the IP Directory had been carried out. This document has been updated during the lifetime of the project to include the IP Directory at the end.

Finally, the EP has established the exploitation strategy for this project and the exploitation objectives. It defined exploitation activities to reach those objectives, and in addition, quantitative and qualitative monitor metrics. The analysis of the impact of the different activities had been carried out [16]. The market identification complementing the one conducted in the EP has been also conducted. This extension of the market identification aimed at recognizing potential markets that might directly benefit from an application of the AGENT Concept, augmenting the project visibility and sustainability.

The dissemination and exploitation activities have been perfomed by the AGENT consortium through knowledge buiding, operationa concept development and verification and validation acitvities as the focus areas. Those are:

- Paper publications. Three research papers have been submitted for the journal publication: “Sensitivity Analysis of Conflict-Free Resolutions for the Airborne Cluster-Ecosystem” to *AIAA Journal of Air Transportation*; “Surrounding traffic complexity analysis for efficient and stable conflict resolution” to *Transportation Research Part C: Emerging Technologies*; “Adaptive aerial ecosystem framework to support tactical conflict resolution” to *The Aeronautical Journal*. The first paper has been accepted for publication, the other two are still under review.
- Conference proceedings. The project team presented the papers at the following conference proceedings: *The 12th USA/Europe Air Traffic Management Research and Development Seminar, Procedia Computer Science, The 6th SESAR Innovation Days, The 7th SESAR Innovation Days*, *EUROSIM2016*, *EMSS2017, Flight Simulation Conference 2017, EIWAC2017.* For more information refer to section 5.2 - Project Publications.
- Workshops - showcase sessions. The AGENT framework has been presented and demonstrated in the following workshops: *EUROCONTROL Agency Research Team workshop on Automation in Air Traffic Management* (23rd October 2017 by Frequentis, Vienna, Austria); *AGENT Workshop at Centro de Investigación Aeroportada de Rozas – CIAR,* to support an efficient Unmanned Aerial System (UAS) Traffic Management (19th December 2017, by CIAR, Lugo, Spain); *AGENT Final Workshop at EUROCONTROL,* to support an efficient air traffic management system involving airspace users’ business models (29th January 2018, by EUROCONTROL - Pollux Conference Room, Brussels, Belgium).

2.3.7 Work Package 7: Project Management

WP7 has been active during the project lifetime. The objective is to ensure an efficient and active coordination of the project through administrative and organizational tasks, and monitoring of the financial project components. Performed activities have included [18]:

- General project administration;
- Preparing and post-processing of European commission reviews from the consortium-side including support in the implementation of recommendations from SJU;

- Preparing, executing, and post-processing of scheduled project meetings;
- Preparation and submission of the management related parts of the reports to SJU.
- Management of financial management platform;
- Preparation of the financial reports to the SJU;
- Controlling of the overall budget;
- Maintenance of the project intranet and data repository for the consortium (Nebula platform), which has been continuously updated, containing all important documents.

2.4 Key Project Results

At the beginning of its lifecycle, the Project was aiming to achieve some of the SESAR Key Performance Indicators (KPIs). The deliverable D1.2: Report on the tools evaluation strategy [2] had elaborated the AGENT expected results and its KPIs that had been aligned with some SESAR KPIs. In summary, all the AGENT benefits will positively reflect to the Airspace Users in the following aspects:

1. A maintained safety level through the SSM preservation in any moment during the ecosystem resolution process, having in mind different scenario complexities. For different ecosystem configurations (number od members, geometry of trajectories, aircraft dynamics), any agreed or compulsory avoidance maneuver by an ecosystem member provides a conflict-free situation in 3D space with respect to a neighboring ecosystem member, achieving the minimum of 5 NM laterally and 1000 ft verticaly in any moment.
2. An improved AUs' cost function, i.e. a higher efficiency in the agreed resolution trajectories assignment, requiring minimal deviations from the original trajectories (RBTs). Comparing to the standard ATC-coordianted resolutions, the AGENT negotiated resolutions require minimal changes in the current headings or vertical rates at a certain time instant previously negotiated among the ecosystem members, that further implies the generation of the minimal extra distance and time in resolution.
3. A deep understanding of spatiotemporal interdependencies between conflicting aircraft considering the surrounding traffic characteristics. For different cluster and ecosystem metrics, i.e. safety buffers (distances), and heading and vertical range changes, the ecosystem size varies as well as the structure of spatiotemporal interdependencies - the manuevering combination among interdependent members and the duration of their conflict interval(s) [7].
4. An active role of the AUs to negotiate a conflict resolution considering different business preferences. The AUs involded in the ecosystem resolution process usually have different operational rules, such as altitude selection, or speed selection. According to these rules, they negotiate the best resolution amadment based on the ecosystem size and trajectory geometries, as well as their predicted states over the ecosystem time [4], [5].
5. A support to the ATC SM tasks with a validated compulsory resolution that could be fired at any moment during the ecosystem time. This aspect particularly denotes the ATC capacity to analytically determine the deadlock instant for any ecosystem configuration, and trigger a set of the compulsory resolutions before this instant, or earlier if necessary, to solve a potential non-agreed situation.
6. An ontology to support an efficient negotiation process through the multi-agent formalism. Developed ontology messaging facilitate the agents' interaction and provides a prompt decision- making process. For future consideration of the ATC position, the ontology structure

can be extended to provide a more active role to ATC driving the negotiation process to efficient and effective resolutions.

7. Coexistence of centrally controlled ATM system with a distributed system in which ATC allows some separation management tasks to be assigned to AU's. These tasks rely on a negotiation process between AU's under the supervision of the ATC. At technological level the negotiation process could be supported at the airside by enhancing the aircraft with agent technologies, or at the ground by enhancing the flight operation centers with agent technology for the negotiation process
8. A benchmarking framework to test CD/CR algorithms. The OD simulation platform has been developed according to the "black-box" principle. That provides the potential users with the possibilities to replace some of the AGENT modules by their own, and test and compare the results coming from the conflict detection and resolution algorithms.
9. A methodological approach for capacity management in the Unmanned Aerial System Traffic Management (UTM) framework. The ecosystem concept based on defined airspace volume, and supported by the MAS conflict negotiated resolutions open the room for implementation to the unmanned aerial systems, whose number of missions is rapidly increasing in the uncontrolled airpace, class G (ICAO). No ATC clearance is provided in this case, so the decentalized and autonomous conflict resolution could be highly applicable.
10. A CR framework to mitigate the propagation of conflict chain reactions. Potential induced conflicts due high dense surrounding traffic is fully analysed by identifying all spatio-temporal interdependencies and computing all feasible manoeuvres of any ecosystem member.
11. A smart monitoring and analytic framework useful to identify hotspots and propose new ATM KPI's considering the analysis of spatio-temporal interdependencies at micro-level. Present functionalities could be easely extended to predict also the interdependencies between ecosystems, providing the baseline for the design of new mitigation mechanisms at strategic level.

One of the project objectives has been an improvement of the airspace capacity. This KPI has been only initialized thought the analysis of developed airborne decision-making tools, but more future research should be performed, especially in terms of its metrics definition. The capacity itself should comprise the ATC position as well, which has not been fully established within the project timeline. However, a good background for this indicator has been set.

Since AGENT has been tailored to the solutions in a multi-aircraft environment, based on the multi-agent systems (MAS) simulation and determined by different complexity indicators at the tactical level, i.e. number of the aircraft inside a computed airspace volume with different state information and relative speed to each other (closure rates), as well as trajectory geometries, the main requirement in providing a set of the conflict resolutions has been maintenance of the standard separation minima (SSM), i.e. the minimum horizontal and vertical separations of 5 NM and 1000 feet, respectively.

As described in the previous sections, and further detailed in the projected deliverables, the AGENT resolutions are divided into agreed and compulsory. Agreed resolutions are generated by the MAS negotiation interaction, and in case that any proposed are acceptable among the sets of the "candidates" (candidate resolutions), they become agreed. The candidate resolutions are provided both by the heading changes and the vertical rate changes. On the contrary, compulsory resolutions are provided at different timestamps during the ecosystem time for triggering in case the negotiation consensus is stopped or not accomplished before the latest moment occurs – the ecosystem deadlock. They are provided only by the heading changes to avoid incoherence (i.e. activation) with the Traffic alert and Collision Avoidance System (TCAS) Traffic Advisories (TA) alerts.

AGENT ConOps [1] was established with a clear vision to integrate the tactical multi-aircraft environment (ecosystem) through the safety nets, the separation management (SM) with collision avoidance (CA). The CA initialization had referred to definition of the deadlock threshold. Many scenario cases during the verification and validation phases have shown that the solutions provided either as agreed or compulsory satisfy the safety requirement.

The AU's efficiency related to CI function change has been analysed as the time or fuel efficiency, either in case of the agreed (MAS-based) or compulsory resolutions. According to the ConOps, the original or planned speed of the aircraft should be maintained, no matter if the horizontal (the heading change) or vertical (vertical rate change) solution is applied. Therefore, in most ecosystem scenarios a unit time increment is assumed to be proportionally followed by a unit fuel increment.

The efficiency analysis has been done for each ecosystem scenario. The goal was to compare different sets/configurations of the agreed resolutions with compulsory ones at the certain timestamps. Thereby, a single agreed solution for an aircraft comprises the preservation of the original Reference Business Trajectory (RBT), meaning that an agent has successfully negotiated its original flight plan within the ecosystem time. The results have shown significant improvement in solutions obtained by the MAS function. A delay, i.e. extra time and extra distance in the resolutions have been significantly which was not the case with compulsory resolution, all comparing with the original RBT segments. Moreover, MAS approach has supported more "degrees of freedom" in the nearby conflict-free solution space, which was the right sign for accomplishment of the satisfying criterion [5].

A complexity of the ecosystem evolution is evaluated based on the decreasing (perishable) rate in number of the candidate RTs over the ecosystem time. A resolution candidate trajectory is defined based on generation of a set of the tactical waypoints (TWPs) and a return waypoint to the RBT. Those TWPs are calculated from an ellipse-based trajectories scheme, in which the aircraft is placed at one foci (a starting point) and a returning point is allocated to the opposite foci. Thus, the TWPs are placed on the different ellipses generated by fixing a certain amount of delay to be introduced to the flight (Figure 2). Then, a pair of the candidate trajectories is evaluated one against another by computing the evolution of the intrinsic complexity as defined in [9]. If two candidate trajectories have a complexity value larger than the values analogous to the TCAS Traffic Advisory, it is rejected.

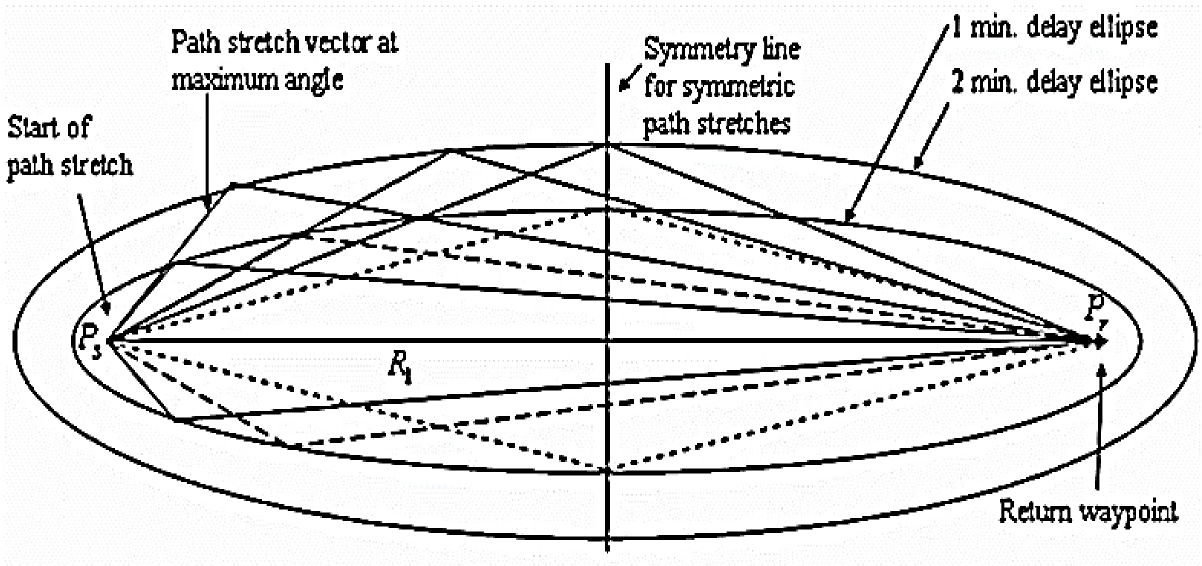

Figure 2: Locus of the tactical waypoints for introducing a given delay to a trajectory

In addition, if the proposed trajectories result in the separation infringements, they are also rejected. The generation of the resolution trajectories is limited to a set of heading changes, including maintaining the RBT. These heading changes vary from -30° to +30° for each aircraft, with steps of 10°. In addition, the delays that could be introduced can go up to 4 minutes, with a 1-minute step. Finally, the number of the available resolution trajectory in each timestamp includes those that can be issued at that specific moment, and all available resolution trajectories that are computed for the future timestamps until the end of the conflict interval. An advantage of the MAS-based solutions is that delay property is not consider.

Throughout a couple of the ecosystem examples, the efficiency KPI is more detailed. The first example has been illustrated in Figures 3 and 4. Figure 3 describes the geometrical configuration of trajectories within Ecosystem 1, in the compulsory resolution mode. The left side of the figure maps the horizontal profile of the ecosystem trajectories, while the right side provides their vertical positions. The ecosystem comprises 3 aircraft, namely EZS1525 (blue), RYR4073 (black) and EZY92LP (orange). EZS1525 and RYR4073 are in the initial conflict. EZS1525 and RYR4073 were both in the cruising configuration flying at FL370. EZY92LP was cruising at FL380. The full lines present the original RBTs and the dotted ones the assigned compulsory trajectories. As it can be seen, the intrinsic complexity metric [9] has shown that for the current timestamp the compulsory resolutions have been triggered for all three aircraft, for EZS1525 (with the delay of 2 minutes), for RYR4073 and EZY92LP (with delay of 1 minute). All aircraft perfomed left-heading changes maneuvers to cooperatively resolve the situation. Within this configuration, the ecosystem has been solved less efficiently than in case of the MAS-applied solution (Figure 4).

Figure 3: Ecosystem 1 - applied compulsory resolutions

For the MAS-applied solution, it is agreed that only EZS1525 performs a resolution amendment with a small heading change (+10°), resulting a shorter extra distance, which made the resolution process significantly optimal and satisficing. In addition, RYR4073 and EZY92LP preserved their RBTs.

Figure 4: Ecosystem 1 - applied MAS resolutions

Nevertheless, a statistical evidence of the solutions comparison has been derived. Table 1 lists some comparable values, and Table 2 depicts the distances at the newly generated/induced Closest Point of Approach (CPA) within Ecosystem 1 for both compulsory and MAS-applied resolutions.

Ecosystem 1			
A/C callsign	Compulsory solution		MAS solution
	Extra distance [NM]	Applied delay [sec]	Extra distance [NM]
EZS1525	15.392	120	0.86138
RYR4073	7.42	60	0
EZY92LP	7.7609	60	0

Table 1: Extra distance and applied ellipse delay for Ecosystem 1 compulsory and MAS-based solutions

Ecosystem 1		
Distance at new CPA [NM]	Compulsory solution	MAS solution
	13.125	5.110

Table 2: Distance at new CPA within Ecosystem 1

After applied either the MAS-based or compulsory solution, once the aircraft amend their conflict segments, they resume to the original RBTs at the computed conflict-free waypoints. These points present the ecosystem removal fixes. Table 1 provides the differences in distance and time between the MAS-applied resolutions and the original segments, as well as the compulsory resolutions with the original segments. The speed values in resolutions phase are preserved, without consideration of the current flight configuration. The MAS solutions obviously provide less deviated solutions, i.e. the resolution trajectories are closer to the RBTs. Furthermore, the MAS solutions are based on the state space analysis, and consequently provide more resolutions capacity and flexibility before reaching the new (induced) CPA.

The second example is described in Figures 5 and 6, respectively. Ecosystem 2 also illustrates a four-aircraft scenario: SAS7296 (blue), SWR831R (red), SVA124 (green) and BER693M (black).

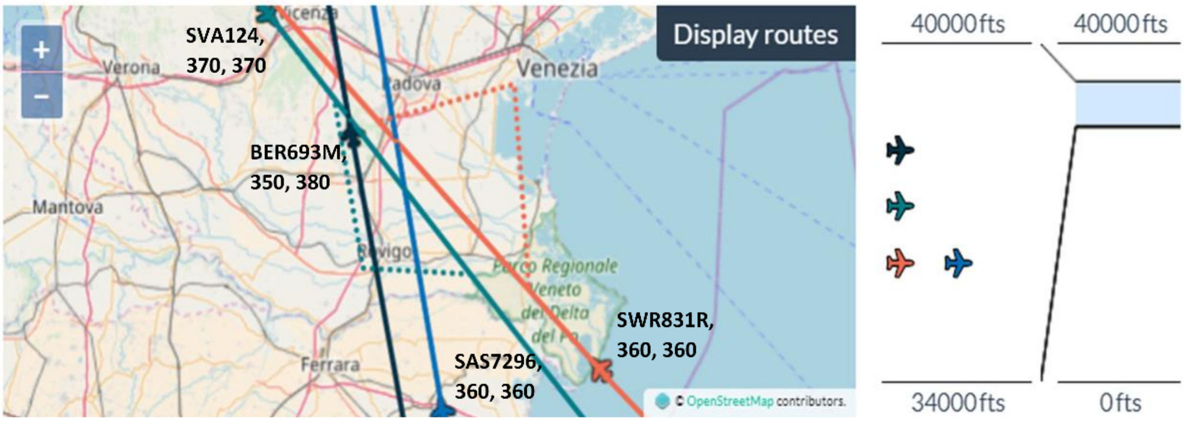

Figure 5: Ecosystem 2 - applied compulsory resolutions

SAS7296 and SWR831R are in the overtaking conflict. Both SAS7296 and SWR831R were in the cruising configuration flying at FL360. SVA124 was cruising at FL370, while BER693M climbing from FL350 to FL380 at the vertical rate of 1250 ft/min. However, according to the compulsory resolution module, the higher complexity values are provided for the potential conflict between SWR831R and SVA124 (Figure 5). Therefore, they are assigned with compulsory resolutions, accumulating the delay values of 120 seconds and 60 seconds for SWR831R and SVA124, respectively. Both aircraft resolved the situation with the right-heading change maneuvers. Other two aircraft completely follow their RBTs during the ecosystem time. On the contrary, Figure 6 provding the MAS-based solution shows a quite different solution. As negotiated, only SAS7296 performs a resulting manoeuvre in the vertical plane, i.e. a descent with a vertical rate of -500 ft/min, and through defined TWPs it resumes to its RBT. The cleared FL for SAS7296 is FL350. The time and distance spent over the new segment are almost negligible and by only this decision, the intrinsic complexity has been removed. Other three aircraft follow their RBTs until the ecosystem removal. Like in the previous example, some statistical values are shown.

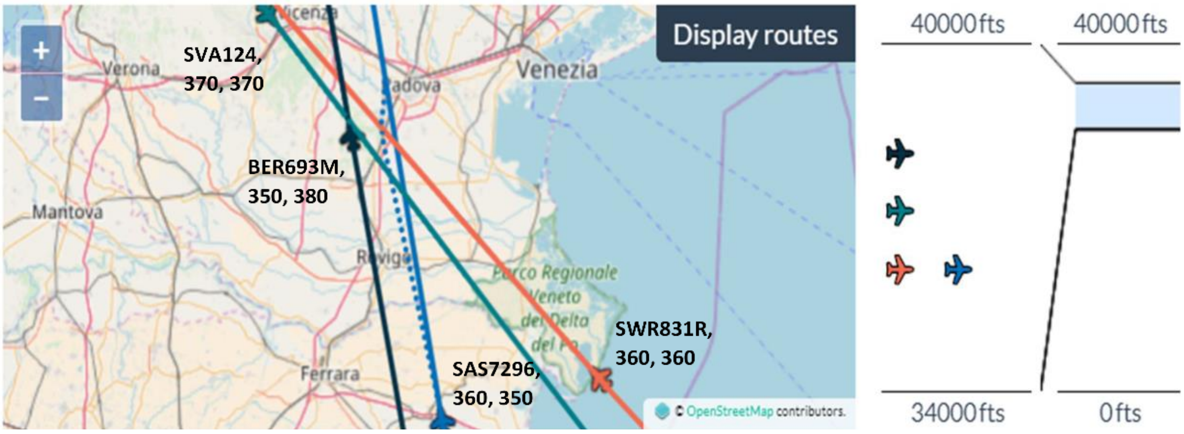

Figure 6: Ecosystem 2 - applied MAS resolutions

Table 3 lists some comparable values, and Table 4 depicts the distances at the induced CPA within Ecosystem 2 for both compulsory and MAS-applied resolutions.

Ecosystem 2			
A/C callsign	Compulsory solution		MAS solution
	Extra distance [NM]	Applied delay [sec]	Extra distance [NM]
SAS7296	0	0	2.65
SWR831R	14.981	120	0
SVA124	7.289	60	0
BER693M	0	0	0

Table 3: Extra distance and applied ellipse delay for Ecosystem 2 compulsory and MAS-based solutions

Ecosystem 2		
Distance at new CPA [NM]	Compulsory solution	MAS solution
	13.885	5.017

Table 4: Distance at new CPA within Ecosystem 2

The MAS solutions obviously provide more applicable system solution, maintain the satisficing criterion. With the minimum deviation and time consumption the safety indicator has been preserved. Finally, the MAS solution again provided more resolutions capacity and smooth transition in its trajectory amendment before reaching the induced CPA.

2.5 Technical Deliverables

Reference	Title, Link and Description	Delivery Date[1]	Dissemination Level[2]
D1.1	Title: Report on AGENT functional and non-functional requirements. Link: http://www.agent-aero.eu/wp-content/uploads/user_uploads/logicdesign/d1.1_report_on_agent_functional_and_non_functional_requirements.pdf) This deliverable describes the ConOps of AGENT framework, starting with the current operational environment supported by a literature review, and complementing the ConOps with functional and non-functional requirements.	29/09/2016	Public
D1.2	Title: Report on the tools evaluation strategy. Link: http://www.agent-aero.eu/wp-content/uploads/user_uploads/logicdesign/d1.2_tools_evaluation_strategy.pdf. This report describes analysis of requirements for the evaluation of the project, identifying the key points that has been used throughout the project to keep track of the expected outcome.	20/11/2016	Public
D1.3	Title: Report on the design of the Open Demonstrator. Link: http://www.agent-aero.eu/wp-content/uploads/user_uploads/logicdesign/d1.3_report_on_design_of_the_open_demonstrator.pdf This document provides a description of the scenarios, the functional design and the input data formalization together with the OD design architecture.	11/01/2017	Public
D2.1	Title: Release of the multi-objective state space analysis tool. This deliverable is a supporting document of the algorithms implemented for the state space analysis functionalities.	24/08/2017	Confidential
D2.2	Title: Release of the multi-agent simulation tool. This deliverable is a supporting document of the algorithms implemented for the multi agent system simulation framework.	04/10/2017	Confidential
D2.3	Title: Release of the Open Demonstrator Link: http://www.agent-aero.eu/wp-content/uploads/user_uploads/logicdesign/d2.3_release_of_the_open_demonstrator_v2.pdf	11/01/2017	Public

[1] Delivery date of latest edition

[2] Public or Confidential

	This deliverable is mainly oriented to the end-user of the OD, illustrating how to feed the traffic data, and how to use the different functionalities by means of a graphical user interface.		
D3.1	Title: Release of the conflict/collision probabilistic forecasting tool. This deliverable is a supporting document of the algorithms implemented for probabilistic forecasting conflicts.	26/12/2016	Confidential
D3.2	Title: Release of the analytics tool. This deliverable is a supporting document of the algorithms on Machine Learning to be implemented for deadlock detection.	12/01/2017	Confidential
D3.3	Title: Release of the resolution trajectory generation algorithms. This deliverable is a supporting document of the algorithms implemented for the generation of compulsory resolutions.	16/03/2017	Confidential
D4.1	Title: Report on the ontology. Link: http://www.agent-aero.eu/wp-content/uploads/user_uploads/logicdesign/d4.1_report_on_the_ontology.pdf This document provides a background on ontologies and formalizes a preliminary ontology to support an efficient negotiation mechanism between agents.	08/02/2017	Public
D4.2	Title: Report on the XML scheme. Link: http://www.agent-aero.eu/wp-content/uploads/user_uploads/logicdesign/d4.2_report_on_the_xml_scheme.pdf This deliverable is a supporting document of the ontology proposed in D4.1 formalized in XML	12/04/2017	Public
D5.1	Title: Verification Report. Link: http://www.agent-aero.eu/wp-content/uploads/user_uploads/logicdesign/d5.1_verification_report.pdf Thus, report introduces the functionalities and requirements regarding the development of new modules which could be implemented into the OD to research new module approaches, including the module interfaces, which are required to work properly with the other modules.	17/11/2017	Public
D5.2	Title: Validation Report. Link: http://www.agent-aero.eu/wp-content/uploads/2018/02/D5.2-Validation-report_v00.01.02.pdf This report discusses results of AGENT validation, describing the validation process and envisaged validation parameters among which a value for assessing the separation between aircraft is proposed together with the track distance and necessary altitude changes for solving conflicts	25/02/2018	Public
D6.1	Title: Set-up of a communication and dissemination strategy and plan.	25/04/2016	Confidential

	This deliverable is a supporting document of the communication and dissemination activities and the metrics used to control the results.		
D6.2	Title: Exploitation Plan. This deliverable is a supporting document of the market analysis and activities to exploit the results achieved in the AGENT project.	27/03/2017	Confidential
D6.3	Title: Report on Exploitation Impact Assessment. This deliverable is a supporting document of the exploitation impact of the activities defined within the Exploitation Plan.	26/03/2018	Confidential
D6.4	Title: Project Website. Link: http://www.agent-aero.eu/. This document presents the AGENT website and its functionalities	30/07/2016	Public
D7.1	Title: Project Management Plan. This document provides the management and planning guides that governed the project execution, establishing the following elements: project scope, activities to be performed according to the project work plan including the definition and the effort and duration, estimation of each one, project schedule, human resources organization and different management processes.	19/10/2016	Confidential
D7.2	Title: Final Project Results Report Present report summarizes the main work implemented in each WP and highlight the main outcomes of the AGENT project providing some quantitive results of ecosystem resolutions obtained by means of compulsory and MAS tools.	26/03/2016	Public

Table 5: Project Deliverables

3 Links to SESAR Programme

3.1 Contribution to the ATM Master Plan

From the beginning of the radio navigation, providing autonomous guidance (Radio Range) or assisted by ground have paved the way towards competing and diverging trends, such as the more recent dichotomy between American free-flight the European gate to gate concepts. The above is also reflected when dealing with bridging the boundaries between separation management and collision avoidance in the foreseen evolution of ACAS. Collision avoidance expansion towards the separation management layer or vice versa has been the opposite headings that researchers have followed with the aim of increasing safety levels. AGENT has tried to break this wheel by introducing harmonisation between airspace users' needs and ATM operational system requirements to improve the conflict management in the fuzzy boundary between separation management and collision avoidance.

On nowadays operations, Air Traffic Controllers' task load are the major factor limiting ATM capacity. Task concentration downgrades the performance system. AGENT has developed an innovative approach that looks for task distribution diverse actors, by developing flexible Decision Supporting Tools (DSTs) which anticipate with longer look ahead times high-complexity scenarios. Air to air negotiation mechanisms have demonstrated to be a potential way forward among for integrating ground and airborne safety nets in a seamless manner, while maintaining safety mechanisms ensuring the safety aim of the ATM system.

AGENT claims for an increased importance of Airspace Users role on the decision-making process but without jeopardising safety as has been encompassed within the European ATM Master Plan, by introducing some objectives which are directly related to Operational Improvements listed enumerated in Table 6.

Code	Name	Project contribution	Maturity at project start	Maturity at project end
CM-0806-C	Improved Compatibility between Ground and Airborne Safety Nets in a Step 3 environment	The OI aims at ensuring the Preservation of situational awareness for pilot and controller without degrading safety. The project has gone beyond the initial aim by implementing a common management of the conflictive scenario, ensuring	TRL0	TRL1

Code	Name	Project contribution	Maturity at project start	Maturity at project end
		a common situational awareness for all actors, together with cooperative and agreed resolutions. Safety is maintained by providing mechanisms for implementing compulsory resolutions clearing conflicts.		
CM-0704	Self-Separation in Mixed Mode	AGENT ConOps contemplate the specific case enunciated by the OI. AGENT first stage does not include the research leading to solve the problem, as it is assumed that aircraft would be equipped and cooperative. However, future AGENT research may contribute to mitigate the impact of aircraft non-equipped for self-separation.	TRL 0	TRL 1
CM-0202	Automated Assistance to ATC Planning for Preventing Conflicts in En-Route Airspace	AGENT methodology includes a stepwise approach for detecting aircraft configuration that may present emergent dynamics that may compromise	Not applicable	Not applicable

Code	Name	Project contribution	Maturity at project start	Maturity at project end
		safety, should a TCAS event occur. Earlier detection of precursors for high-complexity scenarios can increment situational awareness and reduce cognitive burden associated to the controller task-load.		
CM-0205	Advanced support for Conflict Detection and Resolution by Tactical Controller in En-route	AGENT provides technology to detect high interdependent aircraft configurations. In addition, AGENT has developed algorithms that enables controlling delay associated to new resolution trajectories, also mitigating the likelihood of non-coherent sets of resolution trajectories with the ACAS layer.	Not applicable	Not applicable

Table 6: Project Maturity

3.2 Maturity Assessment

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.1	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? Where does the problem lie?	Achieved	Yes. The project has identified three ATM areas to contribute to. These areas are: 1. Coherent transitions between ground and airborne safety nets in a Step 2 / 3 environment [CM-08-06-B and CM-08-06-C]. 2. Capacity bottleneck due to the task allocation for Conflict Management in the Separation Management layer. Tasks associated to the conflict management will be distributed among different agents, including Self-Separation in a mixed-mode [OI CM-0704] 3. Airspace users' role in the decision-making process. Airspace users are already expected to be involved in the planning layer supported by mechanisms such as UDPP. This project proposes a new Operational Improvement where airspace users' involvement on the decision-making process is extended to the separation management layer. The project addresses fundamental academic research dealing with induced conflict in multi-encounter scenarios (Tang, Piera, & Guasch, 2016). In addition, forecasted increments on the air traffic demand will lead to scenarios where the air traffic density will be larger than the TCAS threshold of 0.3 aircraft per square nautical mile, which could derive to induced conflicts due to TCAS unmodeled dynamics. TCAS unmodeled dynamics' impact could be augmented due to lack of coherence between Separation Management and Collision Avoidance. Previous research projects identified these potential weaknesses, such as the PASS project (EUROCONTROL, 2010). The lack of coherence between safety nets has already been identified within the ATM Master Plan (ATM MP) (SESAR JU, 2015) as a required step towards *Advanced Air Traffic Services*. It is reflected on the need for "enhanced air and ground safety nets", also identifying "Advanced separation management" as a key R&D activity.

			Regarding the second bullet point, the ATM MP recognised that the realisation of the SESAR Target Concept would be achieved by the provision of "Advanced air traffic services". Thus, the "future European ATM system will be characterised by advanced service provision, underpinned by the development of automated tools to support controllers in routine tasks" (SESAR JU, 2015). Thus, this aim is covered by the ATM MP in diverse OIs with different objectives, such as: • CM-0104-A (*Automated Controller Support for Trajectory Management*), • CM-0201-A (*Automated Assistance to Controller for Seamless Coordination, Transfer and Dialogue through improved trajectory data sharing*), • CM-0202 (*Automated Assistance to ATC Planning for Preventing Conflicts in En-Route Airspace*) • CM-0205 (*Advanced Conflict Detection and Resolution in En-Route)* CM-0202 recognises that "the heavy workload of tactical controllers is one of the reasons for performance shortfall resulting in capacity problems". AGENT first objective (O1) pursued the development of an automation-based future design of an ATM system supporting a shift from nowadays centralised ATM approach to a distributed one, in which aircraft and ATC collaborate to find an agreed solution considering safety, capacity and cost-efficiency aspects. Additionally, the increasing demand will put more pressure on the system, inducing scalability problems for current solutions. The paradigm-shift proposed by AGENT in its first objective will help to ease the problem by targeting complex scenarios deploying the system resources where they are more effective. Finally, the SESAR Target Concept aims "to achieve high-performing ATM by enabling airspace users to fly their optimum trajectories". The Target Concept aims at involving Airspace Users in the negotiation for agreeing reference business trajectories with ANSPs and airport operators, but limiting their involvement on the separation management. The previous point made the case for including the airspace users as relevant actors on the decision-making process in the separation management. This decision-making process should be based on the application of agents' business models to cover all sensibilities, increasing the overall performance of the system and satisfaction of the stakeholders.
TRL-1.2	Has the ATM problem/challenge/need(s) been quantified?	Partial Achieved – Non Blocking	The criteria are assessed as *Partial – Non-Blocking.* The previous point defined three different problem/challenge/need(s):

			1. Coherent transitions between ground and airborne safety nets in a Step 2 / 3 environment [CM-08-06-B and CM-08-06-C]. 2. Capacity bottleneck due to the task allocation for Conflict Management in the Separation Management layer. Tasks associated to the conflict management will be distributed among different agents, including Self-Separation in a mixed-mode [OI CM-0704] 3. Airspace users' role in the decision-making process. This project proposes a new Operational Improvement where airspace users' involvement on the decision-making process is extended to the separation management layer. For the first bullet point, referenced research identified and quantified scenarios where unmodeled logic failures occur on TCAS multi-encounters. Regarding the second point, the capacity bottleneck has not been directly quantified by the project, but it is identified as one of the expected benefits by the EATM. Specifically, the EATM established that the system shall be capable of handling up to 100% more traffic. Regarding the third point, it is recognised that the AUs should be included for agreeing the RBTs. The benefits of extending the airspace users involvement in the decision-making process to the tactical phase shall be established. The E-ATM established targets for reductions in fuel burn and flight times. In addition, the main aim of the SESAR target concept is "to achieve high-performing ATM by enabling airspace users to fly their optimum trajectories". The project proposes to include AUs in the decision-making process to enable them to pursue that aim. For doing so, it would be required from SESAR to establish mechanisms to determine the optimum trajectory in terms of airspace users' business models, and then, performance targets would be established. In summary, performance targets have to be set for these objectives. The two first challenges are already established as OIs. The third one seeks at defining a new Operational Improvement, to be complemented with a performance target once mechanisms to define optimum trajectories as function of AUs' business models are established.
TRL-1.3	Are potential weaknesses and constraints identified related to the exploratory topic/solution under research? - The problem/challenge/need under research may be bound by certain constraints, such	Partial Achieved, Non-Blocking	The project has identified two constraints which may impact on the solution under research. The first one relates to dependencies of future technological developments, such as: 1. Communication technology for implementing air to air communications and messages exchange. 2. Development of technologies for converting the aircraft into intelligent-agents, enabling the

	as time, geographical location, environment, cost of solutions or others.		negotiation. 3. Development of specific avionic devices handling negotiation and air to air communication. 4. Full development of SWIM. 5. EPP (Extended Projected Profile) updating FMS information to crosscheck the amendment trajectories of ecosystem members. On the same level, the project has identified that the concept would impact in current task allocation in the separation management. ATC is currently recognised as the *separator* in the ATM This role also involves liability. Future task allocation in SM and associated liability aspects shall be further assessed in future research, identifying the new functions and roles for crews and air traffic controllers. The assessment has resulted in Partial-Non-blocking. The first referred aspect, technology dependencies, is considered as non-blocking, because the development of this new concept would require the deployment of these new technologies, but these technologies are not only exclusive of the AGENT concept, but are also aligned with the current digitisation trend in ATM. Regarding the separator role, the AGENT concept could be applied in other operational environments, such as self-separation in mixed mode, where the separator role would be distributed. Lessons learned from these applications may serve as a baseline for gain acceptability of the concept.
TRL-1.4	Has the concept/technology under research defined, described, analysed and reported?	Achieved	The project has progressed through different WPs. The WP1 defined the Concept of Operations [1], how the concept would be evaluated [2] and the functional design of the OD, main tool for the concept evaluation [3]. The D1.1 defined the functional and non-functional requirements for developing the technology underpinning AGENT. The WP2 and WP4 has described and developed the technology for ecosystem identification, negotiation and resolution. In addition, WP4 has developed a unique asset by developing the ontology for the communications among aircraft. In addition, initial analysis and verification reports have been carried out in the main tasks. D2.1 and D2.2 further describe these technologies and the concepts underlying on the AGENT project. The ConOps defined a mechanism to maintaining safety, which was further developed on WP3. Task 3.3 defined the ground concepts for establishing compulsory resolutions in an environment where some aircraft where transiting into the collision avoidance layer. WP5 has carried out the verification and validation activities. A specific tool (the OD) was specifically

			carried out, integrating transversally the processes of the different WPs, allowing a holistic view for performing these activities. WP1 proposed the initial ConOps to be subject to a second iteration to incorporate lessons learned from the project development. These lessons learned will aid to update the functional requirements to define more clearly the scope of the technology solutions for addressing the identified challenges.
TRL-1.5	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM MP Level?	Achieved	The satisfaction criterion has been marked as achieved, based on the following considerations: 1. The SESAR Target Concept aims "to achieve high-performing ATM by enabling airspace users to fly their optimum trajectories". AGENT has extended the airspace users' role, to allow them to decide about their optimum trajectories during the tactical layer, and not only from a planning perspective. 2. AGENT aim was to perform a flight efficient and safe, collaborative and supervised separation management, operationally integrated with trajectory management and collision avoidance. There have been important contributions for identifying traffic configurations with unmodeled dynamics, i.e. that are interdependent. These identifications allow the identification of resolution trajectories avoiding these unmodeled dynamics. In addition, conclusions from previous research projects, such as PASS, have been applied to compute resolutions which would minimise the likelihood of non-compatible resolutions on the late phase of the separation management and the collision avoidance layer. This is a direct contribution to OIs CM-0806-B and CM-0806-C, from operational and technical points of view. In addition, the ecosystem identification process can be introduced as a potential technical solution for complementing current developments regarding CM-0202. Finally, the calculation of aircraft resolutions in AGENT can complement projects which are further developing OI CM-0205. 3. AGENT ConOps can be considered as a starting point considering OI CM-0704 (Self Separation in Mixed Mode), as the case of non-cooperative aircraft is explicitly considered in the development of the concept.
TRL-1.6	Do the obtained results from the fundamental research activities suggest innovative solutions/concepts/ capabilities?	Achieved	Yes. The main contributions of the project are three-fold: - What are these new capabilities? 1. Identify unmodeled properties on the air traffic configurations in a step-wise approach, 2. Provide negotiation skills / capabilities to the airspace users, including an ontology for communications between different agents,

			3. Develop the computation of resolution trajectories where compatibility between resolutions given in the separation management is ensured, regarding potential collision avoidance clearances. - Can they be technically implemented? 1. Yes. The technology is reported in D2.1. 2. Negotiation in multi-agent systems are already present in diverse fields, such as logistics. Multi-agent technologies may be applied in diverse fields around ATM, fomenting competitiveness and fairness. The technology is reported in D2.2, whereas the ontology for negotiation is reported in D4.2. The technology may be tested in simulated environments and widely accepted frameworks, such as INCAS, to test whether these solutions fulfil requirements and recommendations of previous research projects or not. The initial approach is reported in D3.3 and verified in D5.1.
TRL-1.7	Are physical laws and assumptions used in the innovative concept/technology defined?	Not Applicable	• Assumptions are document in the Concept of Operations (D1.1), in the Annex II. They include: removing of level busting by enhanced avionics, more integration between collision avoidance and the autopilot, real-time and secure communications between aircraft, and ATM system providing always the most updated RBT. In addition, for this starting point, the following assumptions are also defined: the ecosystem membership is static, • All aircraft are considered as cooperative and fully AGENT-equipped. • Only en-route operations are considered.
TRL-1.8	Have the potential strengths and benefits identified? Have the potential limitations and dis-benefits identified? - Qualitative assessment on potential benefits/limitations. This will help orientate future validation activities. It may be that quantitative information already exists, in which case it should be used if possible.	Partial Achieved – Non Blocking	The potential benefits are from a safety and operational efficiency points of view. With regard to the former, safety is benefited from the provision of resolutions from the ground safety nets that will not be in contradiction with airborne safety nets. In addition, traffic configuration that may be precursors of undesired concurrence events (i.e. safety event) could be detected and analysed to discard new resolution trajectories that may induce conflicts downstream. From the operational point of view, the main benefit is that the airspace users will be flying according their own business models, allowing them to fly a more optimum trajectory. In addition, the inclusion of the airspace users on the negotiation process will pave the way for the development of AGENT technologies, which can decisively contribute to safety in self-separation environments. The concept requires enablers for its full deployment. The development of these enablers may create some barriers due to the degree of required innovation. However, technology developments in other

			fields, such as logistics or automotive sector can accelerate the development of these technological enablers. Feedback obtained by ATM community about the implementation of AGENT framework is quite diverse. Among the ATC community, main concerns are related to delay the conflict resolution to the last 5 minutes before the CPA, which somehow can be justified because ATC position has not been yet analysed during project execution. On the other side, drone community has been very receptive with present technology for the potential implementation of a U-SPACE.
TRL-1.9	Have Initial scientific observations been reported in technical reports (or journals/conference papers)?	Achieved	Yes. List of published papers: a. Radanovic M., Piera M.A., Koca T., and Saez Nieto F.J., "Self-Reorganized Supporting Tools for Conflict Resolution in High-Density Airspace Volumes." *Twelfth USA/Europe Air Traffic Management Research and Development Seminar*, 2017. b. Radanovic M., and Piera M.A., "Spatially-Temporal Interdependencies for the Aerial Ecosystem Identification." *Procedia Computer Science,* 104 (2017): 242-249. c. Verdonk, Gallego C.E. & Saez, Nieto F.J., "Discussion on Complexity and TCAS indicators for Coherent Safety Net Transitions." In: *The 6th SESAR Innovation Days*, TU Delft, 8-10 November 2016. d. Radanovic M., Piera M.A., Koca T., Verdonk, Gallego C.E., and Saez, Nieto F.J., "Identification of spatiotemporal interdependencies and complexity evolution in a multiple aircraft environment." In: *The 7th SESAR Innovation Days*, Belgrade, 28-30 November 2017. e. Homdedeu J., Mar Tous M., Piera M.A., Koca T., Radanovic M., "A comparative analysis of different methods for identification of the evolution of number of possible conflict-free airspace configurations including multiple aircraft and single conflict." *EMSS2017*, Barcelona, 18-20 September 2017. f. Radanovic M., and Piera M.A., "A Causal Model for Air Traffic Analysis Considering Induced Collision Scenarios." *EUROSIM2016*, Oulu, 12-16 September 2016. g. Radanovic M., Piera M.A., and Koca T., "Adaptive Arial Ecosystem Framework to

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TRL-1.10	Have the research hypothesis been formulated and documented?	Achieved	Yes, the research hypothesis has been documented and formulated on the Section 3.2 of the AGENT Concept of Operations (D1.1), page 64: "Based on previous considerations and functional and non-functional requirements, which will be described in following sections, it is expected that AGENT will be facing during its exploratory lifecycle the following challenges: • Development of coherent and interoperable ground-based (ATC) and airborne DSTs that will preserve smooth transitions from SM to CA in order to find the most optimal and safest resolutions for ecosystem members; • Generation of negotiation procedures, processes and communication protocols (air-air and air-ground) to support AGENT tools; • Introducing the metrics for successful safety nets transitions using the most optimal criteria for the Airspace Users; In addition, the concept assessment introduces new challenges such as: • Identification of complex and representative scenarios to be solved by AGENT tools. • Evaluation of the AGENT concept in scenarios representative of the evolution phases of European ATM system. "
TRL-1.11	Is there further scientific research possible and necessary in the future?	Achieved	Yes. The research has moved towards the scope definition phase (TRL-1). In that sense, the technical solutions will be further defined, involving further research on the following fields: 1. Further research on the compulsory resolution trajectories generation, tailored to the time to the CPA for the different aircraft involved. 2. Integration of trajectory management operational constraints on the AGENT system and the ATC negotiation agent, for a complete trajectory management. 3. Development of functions and roles in the AGENT-based system. 4. Human-factors related research to functions and roles.

			5. Cybersecurity regarding the communications. 6. Development of AGENT-enabled avionics. 7. System emergent properties derived from a competitive-based separation management layer. 8. Introduction of uncertainty management on AGENT technology. 9. Machine Learning algorithm to identify surrounding traffic dynamics. 10. Sensitivity analysis tools when different mix of aircraft are involved in the same ecosystem.
TRL-1.12	Are stakeholders interested in the technology (customer, funding source, etc.)?	Partial achieved-non blocking	The stakeholders participating in the AGENT advisory board has demonstrated interest on the innovative approaches that AGENT is including, such as the negotiation technologies. In addition, AGENT technology has demonstrated potential to be incorporated in the RPAS market, as a solution for decentralised conflict detection and resolution among drones. Special interest for future cooperation's arise from drone operators (i.e. Dronsystems, UK), Engineering companies (i.e. Everis, IDOM), and infrastructure managers (i.e. INTA). The criteria have been assessed as Partial-Non-blocking, as additional engagement from the stakeholders would be beneficial for the acceptability of the concept in future TRL levels. However, is considered non-blocking as the concept and technology developments are targeting specific operational and technological needs included in the E-ATM.

Table 7:Maturity Assessment

4 Conclusion and Lessons Learned

4.1 Conclusions

An overall conclusion is that ER framework provides an excellent opportunity to multi-disciplinary research teams to collaborate in the implementation of new solutions in the ATM field. Debate and discussions with ATM experts, access to data and the flexibility to adapt some objectives of the proposal to more realistic ATM challenges contributes to engage research partners to solve unexpected problems and generate excellent outcomes. There is a common consensus that the implementation of AGENT in the ER framework has unveiled an important amount of research areas in which new results will enhance a decentralized conflict resolution framework integrating the different safety layers, improving most KPI's.

The research work in surrounding traffic analysis, conflict resolution, STCA/TCAS and negotiation agent policies for a decentralized separation management have been very wide ranging from the state of the art on advanced conflict resolution tools to technological implementation of innovative solutions to validate AGENT ideas. The consortium competences in ATC, IT design, optimization, aircraft performance and multi-agent systems has been essential to adapt original proposal on TCAS to a broader ATM environment extending the separation management functionalities by analysing the surrounding traffic.

The differing views of AGENT members in the concept of Ecosystem Deadlock Event (EDE) have been subject of several discussions with relevant interpretations, each one enabling different resolution approaches. It is agreed, that a conservative interpretation of EDE (i.e. an induced collision could emerge) restrict considerably the negotiation time providing a robust framework in which TCAS will not be fired, while a more aggressive interpretation of EDE (i.e. an induced collision cannot be avoided) supports a more fruitful negotiation mechanism in which reaction delays could provoke a TA and a RA. Nevertheless, it is agreed that flexibility can be enhanced by expanding the time window for the ecosystem from the identification of a concurrent event until the deadlock, this one given by time to CPA or by the evolution of the negotiation process or by the number and quality of the feasible resolution trajectories.

To improve the acceptability of AGENT framework as a future more decentralized ATM system supported by a better integration of the safety net layers, AGENT will preserve the ATC situational awareness supporting actively the process and issuing the set of compulsory resolutions at any time before the EDE. Due to time and resources limitation, the ATC position was not the key part of the AGENT scope, instead, the project has been more concerned with the technical viability of the proposed resolution, considering the window of opportunities provided by involving the AU's. It is acknowledged that present results should be extended considering human factors to properly evaluate the task load of ATC within AGENT framework.

Whilst the debate and discussion on the ecosystem technical details during the project has contributed to the challenge of AGENT, the implementation of the OD provides an excellent framework to better quantify and benchmark the different alternative ideas.

Reviews and technical discussions in different international ATM conferences has been considered to improve the original ideas and during the design phase to enhance the OD with future functionalities.

Thus, for example, the use of surrounding traffic complexity metric computed by machine learning techniques is a new functionality that could enhance the monitor agent to force a negotiation consensus between the agents representing the different AU business models. The continuous confrontation with experts and academia has open different future research areas that are summarized at the end of this section.

The consortium has consisted of 4 organisations with a wide range of backgrounds, the total funding available to the project restricted the number of individual involved and time that could dedicate to the project within its 24-month of currency. However, it is recognized that the research engagement with the AGENT challenges has allowed AGENT members to complement in certain tasks the work with the involvement of experts from the consortium organisations to leverage greater effect than would otherwise have been the case.

As part of its closing activities, AGENT has been performing some proactive and targeted dissemination of its results in the RPAS field. In particular, it was organized a workshop with Spanish RPAS community in a new facility nearby Lugo (Spain) and some mission validations works with a drone company are in process. It is envisaged that AGENT results will have a real effect on progress towards the possibilities and realities of RPAS in the near future, providing a tangible contribution in the near to medium term.

4.2 Technical Lessons Learned

The work done in AGENT Project has produced lessons learned, which are summarised below for technical Work packages (Table 8). There are some overlap pings between work package learning since findings feed information to all work packages and there is no clear division where the problem arose and where the consortium team identified the consequences of an upstream problem. One main lesson is the importance of creating the right mechanisms for a mutual learning during the ConOps elaboration in which the different competencies of the members should be seen as the most important asset to create a common understanding of the objectives together with the methods and tools to be adapted/implemented.

Also, another important lesson is the active involvement of an Advisory Board without financial support is difficult. Furthermore, as we have worked on very low TRL it is difficult to find the right (operational) people which have an open mindset and have the possibility to look-forward to “what-if”- scenarios (i.e. they need to imagine how a future world could look like with a tool like AGENT in place) to give valuable feedback. Thus, AB involvement in low TRL projects is questionable if they are asked to contribute to an assessment of the project by reviewing the deliverables and taking an active role in the progress of the project, however their participation in stakeholder workshops (e.g. in parallel to conferences or other events) might be more helpful.

From WP 1	Lessons Learned from Scope definition and User Needs Analysis
	Literature review rely on public deliverables of different on-going and finish projects such as Stream, iFlight, UDPP, ACCORD among others. It would be beneficial to have access to OSED SESAR documents to learn from previous exercises done by SJU members and better understand the SJU interests in order to match the research with SJU member interests.

	It is highly appreciated the "open-mind" framework to slightly adapt the original project objectives to more realistic operational context. Thus, it is considered very positive to focus the efforts in extending CR functionalities to smooth the transfer to TCAS rather than extending TCAS functionalities.
	Early definition of Functional and non-Functional requirements provides an excellent neutral tool to fit the research and future developments into the project framework. Lack of completeness is a source of late integration problems. In AGENT, several integration problems arose due to the implementation of different earth curvature corrections introducing small distortions when using Cartesian and non-Cartesian coordinate systems. An external rigorous analysis of Functional Requirements from different perspectives (IT, Avionics, ATM, ATC among others) will reduce typical integration problems and would contribute to better extend the scope and usability of the tools to be implemented.
	The evaluation strategy has opened a window of opportunity by identifying how results from the exploratory research phase can be taken into the decision-making process for the preparation of future project phase – Industrial Research activities. Again, the evaluation strategy can be very ambitious if only the end-user perspective is considered. The problems to support experiments with the OD can be used to change the functional requirements, or they can be used as a future research/development work.
	The OD design consumed some extra efforts to consider interoperability problems between the modules to be implemented, but also with respect to other data structures well accepted by the ATM community. It would be good and would save a lot of time to the research community the availability of some standardization trends about the scope of CD/CR functionalities and its formalization.
	It is a time-consuming task to analyse traffic data and ATM free to use ATM tools to pre-validate the design of input and output modules and module interfaces. It would help to the research community an effort to distribute an ATM benchmarking framework with data traffic structured according to certain complexity indicator together with different processed KPI's.
From WP2	**Lessons learned from Design and Development of E-TCAS Decision Making Tools**
	Lack of the due rigour in the definition of "Ecosystem Deadlock Event" (EDE) caused different well-justified misinterpretations leading problems during the integration of the modules. Thus, despite modules preserved the interfaces, the interpretation of EDE data was different in each module. Agent do not rely on the mathematical definition of ecosystem traffic dynamics, instead it relies on a quantitative approach of the state space analysis of the surrounding traffic. It is recognized that a preliminary analytical formalization of surrounding traffic or a close cooperation with another ER project dealing with mathematical analysis that could be applied to ecosystem behaviour would help to mitigate integration problems.
	Early discretization of the aircraft heading manoeuvres was positive to reduce the search space of solutions and tackle the state explosion problem identified as a risk.
	Thinking out-of-the-box during the quantitative analysis of ecosystem feasible aircraft manoeuvres was a very positive brain-storming F2F exercise that was the spark for an open future research on conflict-free areas/volumes instead of conflict-free trajectories.

	The flexibility of the ER framework to change optimization criteria described during preparation phase has been very positive to deal with an optimization framework with simplicity, good scalability properties, a mechanism of monitoring and guiding if necessary the search process. Thus, Pareto-optimal optimization proposal was discouraged focussing the optimization efforts in the MAS considering a utility function. Lack of an airline or Airspace user active role in the Advisory Board, or as a consortium member, caused the definition of an academic utility function based mainly on time and fuel consumption to support or reject a resolution manoeuvre during the negotiation process. It would be good to hear from AGENT end-users for a better acceptability of the negotiation process. It is recognized the importance to have them represented in the consortium.
	AGENT designed his own computable ecosystem complexity metrics considering the interdependencies between the aircraft in the surrounding traffic to guide the negotiation process. During validation exercises, it appeared that the way ecosystems were created affected the complexity in the resolution. Consider for example over- taking conflicts generates CR difficulties since resolutions usually are above the scope of physical spatial ecosystem constraints defined in the con-ops. A GAP analysis would reduce this type of problems, but this is unfeasible in a 2-year project duration.
	End-user engagement is critical for the acceptability of the OD. In AGENT it has been organized several discussions between the IT and research members to provide the GUI with all the CD/CR functionalities.
From WP3	**Lessons learned from Development of ATC smart monitoring and Analytics tools**
	Machine Learning is a very powerful approach to predict the ecosystem complexity metric just by identifying surrounding traffic patterns. Technology trust requires a rigorous approach through verification and validation exercises. AGENT project has been over-ambitious and the available person month for the probabilistic forecasting tools did not allowed the researches to rely on the preliminary results to trust the identification of the EDE.
	Thus, results obtained in a reduced number of scenarios have been useful to identify a window of opportunity for the application of ML both in surrounding traffic analysis and in negotiation resolution manoeuvres. However, it has been realized that a huge amount of historical traffic data correlated with ATC directives and aircraft manoeuvres must be guaranteed to succeed.
	Both, in the AGENT proposal and in the KoM it was agreed to consider different types of uncertainties. Unfortunately, sometimes, ATM deterministic problems are so complex that it is not feasible to consider any kind of uncertainty. A trade-off agreement has been reached among the consortium members to develop a robust, useful CR tool and the extend of uncertainty models affecting the results. Since uncertainty is always a keystone aspect between academicians and ATM practitioners, would be good to have a specification of different sources of uncertainties and its severity on the traffic to be considered in any CD/CR ER project. A benchmarking approach would contribute to a better acceptability of the implemented framework.
	Despite the excellent and powerful quantitative tools implemented for compulsory and negotiated ecosystem resolutions, a trade-off between the attainable computational cost and the quality of results (i.e. less optimal solutions) is a must that generates difficulties between researchers and applied oriented consortium members.

	CR and TCAS fragmented framework has been useful to lessen the computational burden of feasible set of compulsory resolutions to avoid contradictory manoeuvres with a potential RA fired by TCAS.
	ATC and Pilot position were out of scope of the AGENT project, which have forced to a trade-off between a conservative approach considering robust reaction time to implement the agreed manoeuvre resolution and the neglect of any delay in the implementation of a resolution consensus.
From WP4	**Lessons learned from Ontology development for communication among agents**
	The specification of the communication protocol between agents using a temporal graphical representation has been very useful not only for the implementation of the agent behavioural rules but also for a better understanding of the negotiation failures during validation exercises.
	Typical chaos in multi agent system applications has been properly avoided at the design time of the ontology, in which both OD designers and optimization academics has been able to reach an agreement to support the search of quasi-optimal solutions.
	The use Coloured Petri Net formalism has been also very useful to check the negotiation patterns and enhance concurrency and distribution decision making mechanisms. Furthermore, since it was accepted that agent negotiation protocol should probably be extended and improved during the validation phase, the early formalization of the ontology using CPN has provided an excellent documentation to test more flexible agent interactions.
	The design of a monitor agent has provided excellent results to guide the negotiation autonomously to consensus results, and it is highly recommended its implementation in decentralized decision-making processes.
From WP5	**Lessons learned from Verification and Validation**
	The modular approach proposed in the OD design has been very helpful in the verification processes identifying more easily bugs and problems module by module avoiding the free propagation of errors between modules and leading to a burden of problems difficult to trace.
	The definition of interfaces has also contributed to an easy verification of the proper implementation of functionalities by means of adapting traffic exercises to the input format of each module and analysing the effects on the outputs considering changes in the inputs.
	Proper documentation of functional and non-functional requirements has contributed also to the verification phase, in which obsolete or out of the AGENT scope requirements were easily identified, among which worthwhile to mention aircraft performance and unexpected behaviour of agents as well as reaction times.
	A certain verification process was very helpful to the consortium team to discuss the benefits and shortages of a Pareto-optimal solutions with respect to the computation of acceptability regions of agents in the ecosystem. As a result, a new functionality was considered to compute conflict-free resolution regions for the negotiation process.
	Validation of the completely realised OD was scheduled to the final phases of the AGENT project, which it is considered an error, since several hidden problems did not arise until the integration phase. Note, that software engineering design processes were properly used during the full phase of the project, but assuming that all partners were using the same earth curvature corrections when implementing the computation of the different functionalities in Cartesian and non-Cartesian coordinate systems was not detected until the integration of all the modules during validation.

	Small distortions introduced in each coordinate system add an extra problem to typical validation problems that arise at integration phase. It is well recognized that intermediate validation tasks should be scheduled at the finalization of any module, or in case of a benchmarking framework, to validate intermediate results considering other frameworks.
	The design should include requirements on the expected performance of the agents during the negotiation process, would make easier some validation tasks.
	Comparison of AGENT results with experimental results in the RPAS sector contributes in the confidence of the validity of the OD functionalities from small scale to large scale. This validation might support RPAS community to plan their tests and their scales.
From WP6	**Lessons learned from Dissemination and Exploitation**
	Among the communication channels it is believed that web has been the most successful medium to distribute information and updates among particular ATM members that were identified in technical conferences, but it is not clear that AGENT website by its own has been able to attract the interest on ATM community.
	Among the dissemination channels it is acknowledged that technical presentations of AGENT project have motivated different collectives to ask for more details. It is true that some ATM communities has been reactive to the AGENT ideas, such as ATC's, since resolution postponement to the last 300 seconds before the CPA is not considered feasible with present technological tools. Regardless of the reaction type, AGENT has always motivated questions among the attendees.
	The exploitation plan proposed was very ambitious, however, considering the low TRL in the manned traffic scenarios, it is considered that the excellent results achieved at the academic level will still require a long journey before its acceptability as a decentralized conflict resolution framework by the ATC community. Extra research work on ATC position, FOC engagement and face validations will be required.
	The true engagement of consortium members has allowed to identify a new exploitation market in which AGENT functionalities could be accepted with less barriers: very low- level drones.
	Despite the TRL is quite low, consortium members have envisaged also the application of AGENT to support AMAN operations as technical enabler, by the selection of the most appropriate method (vectoring, path stretching or holding) tailored to the current situation of the sector at the time of operations. The ATCO would be relieved from the additional workload, acting in a managerial role rather than in a control one.
	All the exploitation AGENT functionalities have been identified, and it is expected that future collaborations in the academic arena will be successfully achieved
From WP7	**Lessons Learned from Project Management**
	Small consortiums with all the consortium members fully engaged in the successful implementation of research objectives creates a friendly atmosphere during brainstorming sessions that foster the identification of most prominent solutions to academic problems. Needless to say, that a small consortium is easy going from the financial and accountability aspects. However, a word of caution must be arisen when technology integration aspects are considered at late stages. These scenarios can force the full team to go over again the

	technologies implemented. Project management should consider extra efforts in the proper coordination of WP's at technological level, not only considering the outcomes.

Table 8: Lessons Learned

4.3 Plan for next R&D phase (Next steps)

The implementation and validation of AGENT OD has unveiled several operational conditions that requires extra research to extend the applicability of AGENT framework as a decentralized conflict resolution in which airspace users are enhanced in a resolution negotiation process. On the other hand, there are several research and innovation topics that were out of the scope of the AGENT proposal and should be considered in future research to reach enough maturity. Bellow are summarized both future research topics.

Next Steps for AGENT OD:

1. *Causal Based Ecosystems*: Present implementation of ecosystems rely on a spatial bounded volume around a CPA in which all surrounding traffic with a potential interdependency with the conflict pairwise trajectories belong to the ecosystem together with those trajectories with interdependencies with new ecosystem members. This spatiotemporal analysis is exhaustive but bounded in Time (i.e. LAT) and Space (i.e. Cluster around the CPA).

   Validation exercises unveiled that the spatiotemporal analysis of interdependencies cannot be constrained to those trajectories inside a spatial box, instead it should be considered the potential downstream-upstream interdependencies. Note for example the unstable dynamics generated when 2 ecosystems are located in such a distance that the resolution in one ecosystem could amend a trajectory that originally had no interdependency in the other ecosystem so it was not considered as ecosystem member.

   Thus, ecosystems creation should rely on a true causality border-less analysis of upstream-downstream dynamics. Somehow, in the PARTAKE project (ER 699307) a causal model has been implemented to identify the mentioned dynamics in which time-stamp plays an important factor for mitigating tight interdependencies. The knowledge acquired in PARTAKE will contribute to a more robust analysis and implementation of the ecosystem concept. Thus, an ecosystem could contain more than one detected conflict and the negotiation resolution mechanism should consider all the effects between the surrounding traffic dynamics. It is worthwhile to note that this problem emerged several times when validating present traffic, and it will have a negative impact when density is increased.

2. *Piecewise linear trajectories*: It has been considered the user preferred trajectory as a set of consecutive segments linking waypoints and additional pseudo waypoints computed by the FMS to build the vertical profiles and lateral transitions. The hypothesis of linear segments to inside the ecosystem is not true for most of the traffic analysed. It has been observed that most segments are takes a duration smaller than 300 seconds (AGENT Look-Ahead-Time), due among other causes the fly-by trajectory computations.

   The Ecosystem creation should be extended assuming piecewise linear segments. It is recognized that the original CR approach was based on discretization of heading manoeuvres which would introduce a lot of problems to accept piecewise linear segments. An updated approach considers the computation of areas as a continuous function to enable the use of analytical computation (not just quantitative approach). Thus, piecewise linear segments can be supported but new functionalities should be implemented in the "Potential Conflict Detection" module, "Cluster Identification" module and "Multi Agent System" module.

3. *All kinds of resolution trajectories:* At present, the negotiation process and the compulsory resolution model, identify a heading for each ecosystem member that must perform a manoeuvre considering also the resume manoeuvre to the original trajectory within the ecosystem airspace volume (+- 300 second to/from CPA). There are several conflicts such as overtaking in which the manoeuvre exceeds the ecosystem airspace volume. The Multi Agent System module implementing the negotiation mechanism should be extended with more resolution algorithms for a better acceptability of AGENT in any surrounding traffic scenario.

4. *Implementation of a search algorithm to reduce the computation time*. The state space analysis of surrounding traffic and the computation of a set of conflict resolution manoeuvres for agent negotiation rely on an exhaustive search with an important computational burden. There are several search algorithms such as Tabu search and Simulation Annealing (among others), which could be implemented to drive the search to feasible regions and avoid time- consuming exploration of areas with poor chances to provide a resolution.

5. *Uncertainty models for the resolution trajectories*: Present implementation of the OD modules, assumes the computation of a fixed CPA (Closest Point of Approach), and all the cluster and ecosystem membership analysis together with the computation of resolution manoeuvres (both in the compulsory module and in the MAS module) implements the functionalities according to the identified CPA. Despite it is not expected a huge uncertainty in the trajectories within a LAT of 300 seconds, it must be considered the uncertainties affecting the CPA computation to obtain a more robust evaluation of the decentralized resolution system. It is proposed to describe CPA as a time dependent small region inside the Ecosystem, so the limits of the regions will be used for a robust resolution.

Next Steps for AGENT Framework:

1. *Ecosystem Deadlock Event analytical definition*: Safety has been an indicator that cannot be compromised in any traffic scenario. AGENT framework relies on a quantitative approach to estimate the deadlock event each time an ecosystem is created. Since quantitative methods lack of a rigorous analysis to guarantee a "timed induced collision-free scenario" it is considered important to develop an analytical approach to identify time requirements that must be preserved in any ecosystem before firing a compulsory resolution. Qualitative analysis of the deadlock event will guarantee safety levels while will compute the negotiation time limit without introducing latent capacity due to over-conservative negotiation time limit.

2. *Design a surrounding traffic complexity metric*: It has been reported in D3.2 a metric for resolution complexity, which provides timed information about potential feasible resolution. This metric has been very useful for the monitor agent to understand the perishable resolution speed of the ecosystem. However, considering the computation of areas instead of amount of discretized resolutions, a new metric should be elaborated to understand the complexity of the negotiation process to avoid a compulsory with respect to the surrounding traffic complexity. Aspects such as speed differences between ecosystem members could increase considerably the difficulties to reach a consensus with respect to another ecosystem with a

similar traffic but similar aircraft speeds.

3. *Model Aircraft Performance*: Considering AGENT proposal as a ER project with low TRL, the implemented framework has not considered different aircraft performance, instead all the modules consider just 1 type of medium aircraft performance. To tackle more realistic scenarios AGENT framework should be enhanced with the performance of a mix of medium and heavy aircraft to evaluate if the decentralized framework is still robust, or is sensible to the mix of ecosystem members, in which case MAS module functionalities should be extended.

4. Resolution areas: The computation and segmentation of feasible areas inside the ecosystem has been an excellent innovative approach to compute analytically bundles of resolutions with a better computational efficiency but there are several open issues that should be considered: Adaptation to piecewise linear segments, refine the calculation method of the inner area border considering time not just space, extend the resolution areas to volume resolution segmentation (useful for drone applications) and introduce possibility to combine delays with speed adjustments.

5. *Agents with learning capability*: Agents behavioural rules have been implemented considering airspace users' business models to compete during the negotiation process. It is recognized through informal talks with ATM experts, that AU's will enhance their agents with learning capabilities to constantly improve their negotiation profile to succeed with the best resolution (i.e. force a manoeuvre of other aircraft and maintain the RBT). Given the impact of agent learning in the negotiation process (i.e. no consensus reached, or unstable negotiation cycles) it is considered important to improve the ontology and enhance the monitor agent with extra functionalities to tackle agent-learning behaviours.

6. *Extend MAS with realistic AU's business models supported at Flight Operation Centres*: Despite the resolution negotiation mechanism could be embedded in the aircraft, so providing intelligent functionalities to ecosystem members, it is also well accepted that the agent negotiation should take place between flight operation centres which have a more broader view of business acceptable resolutions considering fairness and equity criteria. Extending MAS to FOC's for the negotiation resolution mechanism would contribute to a better acceptability and a key factor to engage AU's.

7. *Machine Learning for Surrounding Traffic Complexity*: To enhance the acceptability of AGENT framework starting the negotiation resolution mechanism 300 second before the CPA, it is important to obtain the maximum information at the time the ecosystem is created in order to maintain always the ecosystem above safety criteria. The implementation of a machine learning algorithm to identify traffic patterns and negotiation patterns would help to reach an early consensus and absorb any late moment uncertainty.

8. *Drones Application*: U-SPACE provides an excellent opportunity to validate the ecosystem resolution functionalities embedding agent negotiation mechanism in the drone architecture, supported by M2M technology. The main differences regarding aircraft performance, very short linear segments, and the business model, introduces some important changes in the modules that properly adapted and validated could contribute to a decentralized conflict resolution system for RPAS.

9. *ATC position*: It is of high relevance importance to consider the ATC position in the AGENT framework. The limited time and resources in ER projects made it difficult to reach the role of

ATC in AGENT. Despite it has been considered that the situational awareness of ATC is maintained and that a HMI will provide monitoring and compulsory resolutions of any ecosystem, the project should be extended considering the ATC human factors to take over control from monitoring to issuing manoeuvre directives, the relevant information they would like to monitor, the right HMI that would help monitoring, and the reaction time of all involved actors.

10. *Pilot position*: Again, the cockpit information neither the role of pilot in the AGENT framework has not been considered in this ER project due to time and resource limitations. Previous experiments in ASAS reported a poor acceptability for the pilot community. Extra work is required to remove barriers and enhance enablers considering the pilot tasks.
11. *Training Material*: An important aspect to leverage the functionalities implemented in the OD to be used as a reference framework by the Academic, ATC and Pilot communities is the preparation of training materials to get used to the agent negotiation mechanism, and allow them to take an active role in the future improvements of the framework.

5 References

5.1 Project Deliverables

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Appendix A

A.1 Glossary of terms

Term	Definition	Source of the definition
ATM	The dynamic, integrated management of air traffic and airspace safely, economically and efficiently through the provision of facilities and seamless services in collaboration with all parties.	*EUROCONTROL ATM Lexicon: https://ext.eurocontrol.int/lexicon*
ATM System	A system that provides ATM through the collaborative integration of humans, information, technology, facilities and services, supported by air and ground- and/or space-based communications, navigation and surveillance.	*EUROCONTROL ATM Lexicon: https://ext.eurocontrol.int/lexicon*
Conflict	Any situation involving an aircraft and a hazard in which the applicable separation minima may be compromised.	*SKYbrary Aviation Safety: https://www.skybrary.aero*
MAS	A multi-agent system (MAS) is a system composed of interacting intelligent agents within one environment. Intelligent process may include some methodology, functional or procedural approach, or algorithmic search.	*Wikipedia: https://en.wikipedia.org*
RBT	The business trajectory which the airspace user agrees to fly and the ANSP and Airports agree to facilitate (subject to separation provision).	*EUROCONTROL ATM Lexicon: https://ext.eurocontrol.int/lexicon*
SSM	The minimum displacements between an aircraft and a hazard which maintain the risk of collision at an acceptable level of safety.	*SKYbrary Aviation Safety: https://www.skybrary.aero*
SESAR	Single European Sky ATM Research Programme	SESAR Joint Undertaking: http://www.sesarju.eu
SJU	SESAR Joint Undertaking (Agency of the European Commission)	SESAR Joint Undertaking: http://www.sesarju.eu
Trajectory	The description of movement of	*SKYbrary Aviation Safety:*

	an aircraft both in the air and on the ground including position, time, and at least via calculation, speed and acceleration.	*https://www.skybrary.aero*
Trajectory (4D)	The 4D trajectory is a set of consecutive segments linking published waypoints and/or pseudo waypoints computed by air or ground tools (airline pseudo FMS, aircraft FMS, ground Trajectory Predictor) to build the lateral transitions and the vertical profiles. Each point is defined by a longitude, latitude, a level and a time with associated constraints where and when required.	*EUROCONTROL ATM Lexicon: https://ext.eurocontrol.int/lexicon*

Table 9: Glossary

A.2 Acronyms and Terminology

Term	Definition
AB	Advisory Board
ACAS	Airborne Collision Avoidance System
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATM	Air Traffic Management
AU	Airspace User
CA	Collision Avoidance
CD	Conflict Detection
ConOps	Concept of Operations
CPA	Closest Point of Approach
CR	Compulsory Resolution
DDR	Demand Data Repository
DMT	Decision Making Tools
DST	Decision Support Tools

EDE	Ecosystem Deadlock Event
EI	Ecosystem Identification
EP	Exploitation Plan
ER	Exploratory Research
F2F	Face-to-Face
FMS	Flight Management System
FRA	Free Route Airspace
GUI	Graphical User Interface
IPRM	Intellectual Property Rights Management
M2M	Machine-to-Machine
MAST	Multi-Agent Simulation Tool
MP	Master Plan
OD	Open Demonstrator
PBO	Performance Based Operations
RPAS	Remotely Piloted Aircraft Systems
RBT	Reference Business Trajectory
SESAR	Single European Sky ATM Research Programme
SJU	SESAR Joint Undertaking (Agency of the European Commission)
SM	Separation Management
SSM	Standard Separation Minima
STCA	Short Term Conflict Alert
SWIM	System Wide Information Management
TCAS	Traffic alert and Collision Avoidance System
TM	Trajectory Management
TRL	Technology Readiness Level
WP	Work Package

Table 10: Acronyms and terminology