Universitat Autònoma de Barcelona

ADAPTIVE SELF-GOVERNED AERIAL ECOSYSTEM BY NEGOTIATED TRAFFIC

MARKO RADANOVIC

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ADAPTIVE SELF-GOVERNED AERIAL ECOSYSTEM BY NEGOTIATED TRAFFIC

MARKO RADANOVIC

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Campus Universitari, s/n

08193 Bellatera Barcelona SPAIN

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Dr. Miquel Angel Piera Eroles, a full time professor at Universitat Autònoma de Barcelona

CERTIFIES:

That the doctoral thesis entitled "**Adaptive self-governed aerial ecosystem by negotiated traffic**", presented in partial fulfilment of the requirements for obtaining the degree of Doctor of Philosophy, embodies original work done by **Marko Radanovic** under his supervision.

Dr. Miquel Angel Piera Eroles
Logistics and Aeronautics Unit
Department of Telecommunications
and Systems Engineering
Universitat Autònoma de Barcelona

Great moments are born great opportunity.

Nikola Tesla (1856 – 1943)

Abstract

In recent years, several important research projects under the Single European Sky Air Traffic Management (ATM) Research and the Next Generation Air Transportation System initiatives, addressing the automation in ATM have been conducted. Those initiatives have envisaged the automation as a process driven by the overall ATM performance, focused on the system objectives and limitations. In a broader scope, the objectives are defined as a provision of the required separation between aircraft to meet the safety target levels, while the traffic competitiveness is maintained by means of an efficient system, environmentally friendly and socially valuable.

An increased operational density together with a lack of the air traffic control (ATC) capacity, in handling a higher traffic complexity, essentially imposes a separation provision to be implemented as cooperative and distributed, enaging also the airspace users (AUs). In this context, it is necessary to shift from a purely centralized tactical intervention model towards a more efficient strategic planning and proactive tactical operations, which assume significant changes of the roles and responsibilities of all involved stakeholders. That anticipates an operationally seamless integration of the safety net mechanisms and procedures in such a way that any pair of aircraft involved in a conflict, together with the surrounding traffic aircraft, behave as a stable and efficient, conflict-free air traffic system.

The research work in this thesis elaborates a novel safety net framework relying on the concept of aerial ecosystems to transform the non-coordinated targets between separation management at the tactical level and collision avoidance at the operational level, into a cooperative and efficient, conflict-free system. 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 among involved aircraft and its ever-changing environment. The thesis comprises few analytical outcomes utilized by the means of quantitative methods for identification of the spatiotemporal interdependencies and computation of the total ecosystem-level solutions and deadlock within available ecosystem time. The analytical methods are applications-oriented rather than a theory-based, developed with a quantitative and discrete modelling approach, and customized to the current traffic demands and the operational environment.

As a result, the ecosystem framework has an ability to further explore the potential resolution capacity in a search space of the system solutions. A decreasing rate of the available ecosystem resources and an elapsed time describe a potential path in an explicit determination of the resolution dynamics, meaning that each missed moment in making a resolution agreement might reprobate in a less number of the conflict-free maneuvers, but also maintain or increase them in some circumstances. The approach has shown a significance in providing the time capacity for a set of certain maneuvers at the operational level, when a severity of the conflict situation occurs very rapidly. With a causal increment in a number of ecosystem aircraft and diverse trajectory geometries, the structure of spatiotemporal interdependencies becomes larger which can produce less resolution capacity and a shorter decision-making time.

The modeling methodology can be deployed as both the airborne and ground-based decision support tool. Follow-up research will be multi-directionally formalized throughout conceptual advancement of the resolution regions, integration of the aircraft performance models, development of a machine learning model for the surrounding traffic complexity, and implementation of the cooperative and competitive ecosystems for unmanned aerial vehicles.

Resumen

En los últimos años, se han llevado a cabo varios proyectos de investigación importantes en el marco de las iniciativas de Single European Sky Air Traffic Management (ATM) Research y Next Generation Air Transportation System, que abordan la automatización en ATM. Esas iniciativas han previsto la automatización como un proceso impulsado por el rendimiento global de ATM, centrado en los objetivos y limitaciones del sistema. En un ámbito más amplio, los objetivos se definen como una disposición de la separación requerida entre las aeronaves para alcanzar los niveles de seguridad objetivo, mientras que la competitividad del tráfico se mantiene mediante un sistema eficiente, respetuoso con el medio ambiente y socialmente valioso.

Una mayor densidad operativa junto con la falta de capacidad de control de tráfico aéreo (ATC), al manejar una mayor complejidad de tráfico, impone esencialmente una disposición de separación que se implementará como cooperativa y distribuida, incorporando también a los usuarios del espacio aéreo (AU). En este contexto, es necesario pasar de un modelo de intervención táctica puramente centralizado a una planificación estratégica más eficiente y operaciones tácticas proactivas, que supongan cambios significativos en los roles y responsabilidades de todas las partes interesadas. Eso anticipa una integración operacionalmente fluida de los mecanismos y procedimientos de la red de seguridad de tal manera que cualquier par de aeronaves involucradas en un conflicto, junto con la aeronave de tráfico circundante, se comporten como un sistema de tráfico aéreo estable, eficiente y libre de conflictos.

El trabajo de investigación en esta tesis elabora un nuevo marco de red de seguridad que se basa en el concepto de ecosistemas aéreos para transformar los objetivos no coordinados entre la gestión de la separación a nivel táctico y la prevención de colisiones en el nivel operacional, en una cooperativa y eficiente, libre de conflictos sistema. Los ecosistemas aéreos se pueden entender como un paradigma de los complejos sistemas adaptativos, en los que las trayectorias de los aviones cambian y evolucionan con el tiempo debido a las interacciones entre las aeronaves involucradas y su entorno en constante cambio. La tesis comprende pocos resultados analíticos utilizados por medio de métodos cuantitativos para la identificación de las interdependencias espaciotemporales y el cálculo de las soluciones totales del nivel del ecosistema y el punto muerto dentro del tiempo del ecosistema disponible. Los métodos analíticos están más orientados a las aplicaciones que a la teoría, desarrollados con un enfoque de modelado discreto y cuantitativo, y personalizados según las demandas actuales de tráfico y el entorno operativo.

Como resultado, el marco del ecosistema tiene la capacidad de seguir explorando la capacidad de resolución potencial en un espacio de búsqueda de las soluciones del sistema. Una tasa decreciente de los recursos del ecosistema disponibles y un tiempo transcurrido describen un camino potencial en una determinación explícita de la dinámica de resolución, lo que significa que cada momento perdido al hacer un acuerdo de resolución podría repercutir en un menor número de maniobras libres de conflicto, pero también mantenerlos o aumentarlos en algunas circunstancias. El enfoque ha demostrado la importancia de proporcionar la capacidad de tiempo para un conjunto de ciertas maniobras a nivel operacional, cuando la gravedad de la situación de conflicto ocurre muy rápidamente. Con un incremento causal en una serie de aeronaves de ecosistema y diversas geometrías de trayectoria, la estructura de las interdependencias espaciotemporales se hace más grande, lo que puede producir una menor capacidad de resolución y un tiempo de toma de decisiones más corto.

La metodología de modelado se puede implementar como herramienta de apoyo a la decisión tanto en el aire como en tierra. La investigación de seguimiento se formalizará multidireccionalmente a través del avance conceptual de las regiones de resolución, la integración de los modelos de performance de la aeronave, el desarrollo de un modelo de aprendizaje automático para la complejidad del tránsito circundante y la implementación de ecosistemas cooperativos y competitivos para vehículos aéreos no tripulados.

Resum

En els últims anys, s'han dut a terme diversos projectes de recerca importants en el marc de les iniciatives de Single European Sky Air Traffic Management (ATM) Research i Next Generation Air Transportation System, que s'ocupen de l'automatització en caixers automàtics. Aquestes iniciatives han previst l'automatització com un procés impulsat pel rendiment general de l'ATM, centrat en els objectius i limitacions del sistema. En un àmbit més ampli, els objectius es defineixen com una disposició de la separació necessària entre aeronaus per assolir els nivells objectiu de seguretat, mentre que la competitivitat del trànsit es manté mitjançant un sistema eficient, respectuós amb el medi ambient i socialment valuós.

Una major densitat operativa, juntament amb la manca de capacitat de control del trànsit aeri (ATC), en el maneig d'una major complexitat del trànsit, imposa bàsicament una disposició de separació que s'ha d'implementar com a cooperativa i distribuïda, a més d'utilitzar usuaris d'espai aeri (AU). En aquest context, cal passar d'un model d'intervenció tàctica purament centralitzada cap a una planificació estratègica més eficient i operacions tàctiques proactives, que assumeixen canvis significatius dels rols i responsabilitats de tots els grups d'interès implicats. Això anticipa una integració operativa i fluida dels mecanismes i mecanismes de la xarxa de seguretat de tal manera que qualsevol parell d'avions implicats en un conflicte, juntament amb els avions de trànsit que l'envolten, es comporten com un sistema de trànsit aeri estable i eficient i sense conflictes.

El treball d'investigació d'aquesta tesi explica un nou marc de seguretat que es basa en el concepte d'ecosistemes aeris per transformar els objectius no coordinats entre la gestió de la separació a nivell tàctic i l'evitació de col·lisions a nivell operatiu, en una cooperativa i eficient, sense conflictes sistema. Els ecosistemes aèries es poden entendre com un paradigma dels sistemes adaptatius complexos, en què les trajectòries aeronàutiques canvien i evolucionen amb el pas del temps a causa de les interaccions entre els avions implicats i el seu entorn canviant. La tesi comprèn pocs resultats analítics utilitzats pels mètodes quantitatius per a la identificació de les interdependències espaciotemporals i el càlcul de les solucions totals de nivell de l'ecosistema i el punt mort en el temps de l'ecosistema disponible. Els mètodes analítics són orientats a les aplicacions en comptes d'un basat en la teoria, desenvolupat amb un enfocament de modelització quantitatiu i discret, i personalitzat a les demandes de trànsit actuals i a l'entorn operatiu.

Com a resultat, el marc de l'ecosistema té la capacitat d'explorar encara més la possible capacitat de resolució en un espai de cerca de les solucions del sistema. Un percentatge decreixent dels recursos disponibles de l'ecosistema i un temps transcorregut descriuen un camí potencial en una determinació explícita de la dinàmica de resolució, el que significa que cada moment perdut en la realització d'un acord de resolució podria repercutir en un nombre menor de maniobres lliures de conflictes, però també mantenir o augmentar-les en algunes circumstàncies. L'enfocament ha mostrat una importància en proporcionar la capacitat de temps d'un conjunt de certes maniobres a nivell operatiu, quan la gravetat de la situació del conflicte es produeix molt ràpidament. Amb un increment causal en diversos avions d'ecosistemes i diverses geometries de trajectòria, l'estructura de les interdependències espaciotemporals es fa més gran que pot produir menys capacitat de resolució i un menor temps de presa de decisions.

La metodologia de modelatge es pot implementar com a eina de suport a la decisió a l'aire i en terra. Les investigacions de seguiment es formalitzaran en múltiples direccions a través de l'avanç conceptual de les regions de resolució, la integració dels models d'actuació de l'avió, el desenvolupament d'un model de modelatge de la complexitat del trànsit circumdant i la implementació dels ecosistemes cooperatius i competitius per a vehicles aeris no tripulats.

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1. Introduction

The air traffic management (ATM) system is a safety critical, complex socio-technical system [1], [2]. ATM encompasses all airborne and ground-based functions and services required to ensure the safe and efficient movements of all airspace users. It is composed of three main functions [3]: air traffic services (ATS), air traffic flow and capacity management (ATFCM), and airspace management (ASM), which are all principally ground-based.

The ATM system comprises all the resources necessary to support different aircraft operations, shared airspace and airports compatible, in a safe, efficient and orderly manner. Each service, mentioned above, has a role aiming at that purpose. ASM is expected to plan in a strategic level the ATM organization and structure, keeping in mind that airspace shall be a continuous, flexible and responsive to short-term changes in the airspace user needs. The ATFCM function shall guarantee the correct balance between demand and capacity of flows crossing airspace and system resources. Finally, ATS is meant to aid and ensure all tactical activities supporting safety and efficiency of air traffic, and it consists of air traffic control (ATC) services, flight information services and alerting services.

Different ATM functions and the related services organize the airspace and air traffic depending on the predicted demand and capacity. The airspace is currently divided vertically and laterally in volumes (structured in ATC sectors) handled by air traffic controllers, who can manage a limited number of aircraft. As traffic increases, sectors are restructured into smaller volumes. This method is limited in high density areas where the size of the sector restricts the resolutions needed to solve any conflicts among aircraft. Thus, when this level is reached, and traffic demand exceeds capacity, ATFCM regulations are activated for limiting the traffic through a sector. This concept results in an insufficiently flexible and fragmented airspace affecting an optimality in the trajectory management (TM) functions. The future ATM system should overcome problems associated to this kind of organizational structure shifting from the airspace-based to a trajectory-based organization, in which the system is devoted to providing the compatible and efficient trajectories for all airspace users [4], [5].

Long-term forecasts with horizons of up to 20 years are clearly prone to changes due to economic, political and social conditions, as indicated in the 2013 edition of the EUROCONTROL study, “Challenges of Growth” [6]. The study estimates an increment of between 3.4 and 5.2 million flights more in 2030 compared to the 2010 Statistics and Forecasts (STATFOR) long-term forecasts upon which the 2nd Edition of the Master Plan (2012) was built. The reasons offered for the change in forecast are many, but most notable among them are a series of interrelated factors such as high volatility in air traffic demand since 2008, the economic downturn, a sharp reduction in airport expansion plans and the growth of major airport hubs.

Present ATM research programs envisage a 73% growth in capacity in 2020 compared to 2005 in the European transport network. EUROCONTROL forecasts a 41% increase in capacity between 2007 and 2030 [6]. Besides a lack of runway capacity in some airports during peak time periods, present en-route airspace management procedures are a major constraint to air traffic capacity. The en-route capacity depends not only on spatially geometrical separation criteria between aircraft, but also the air traffic controllers’ workload. To preserve the safety distance between aircraft, sectors are managed by a team of controllers (two, by default) that monitor the flights progress within the sector, communicates with the aircraft, and provides instructions if safety distance between aircraft is not preserved.

It is evident that system stability and efficiency associated with separation assurance in some region of airspace will depend on the complexity of traffic flow across that region. Airspace complexity, also referred to as dynamic density, has been characterized by several research studies [7], [8], [9], [10]. Despite these studies, there is no universal definition for the airspace complexity. A number of aircraft in the airspace of interest together with the trajectory geometries are generally a key factor in defining the airspace complexity. Other factors may include relative or absolute velocities of aircraft, as well as proximity to other aircraft, sector boundaries, weather or terrain conditions.

The main ATM mission is to provide a set of services to preserve the required separation between aircraft to meet safety target levels, while competitiveness of the air traffic is maintained by means of an efficient system, environmentally friendly and socially valuable [11], [12]. Safety performance indicators are achieved through a set of mechanisms for the prevention of imminent hazardous situations that could evolve towards major incidents or even accidents [13]. These mechanisms are known as safety nets [14]. Within the ATM system, safety nets are intended to provide timely alerts to controllers or pilots of an increased risk to flight safety [15], and are structured in four main layers according to an operational time horizon:

- Strategic level: hours before flight departure, a ground regulation can be issued if a demand is greater than the available capacity and the system is in a maximum deployment state. By limiting the number of aircraft crossing an ATC sector, the probability of a separation minima infringement can be reduced, but it cannot guarantee conflict-free trajectories.
- Tactical level: medium term conflict detection (MTCD) function usually starts 20 to 15 minutes prior to a potential safety event occurrence, in which the air traffic controllers issue directives to one of the aircraft involved in a conflict to preserve safety distance.
- Pre-operational level: the short-term conflict alert (STCA) system usually fires a warning to the ATC 120 to 90 seconds before a collision might occur.
- Operational level: traffic alert and collision avoidance system (TCAS) is the last service to avoid a pairwise collision. The main difference with respect to previous safety net layers is that TCAS is airborne system that functions independently of the ground-based safety layers and provides collision avoidance advisories for a broad spectrum of aircraft types.

Current ATM system is basically a ground-based system with three different levels of operational management tasks:

- Airspace management,
- Demand/capacity balancing or air traffic flow and capacity management, currently also in charge of the trajectory management (TM),
- Separation management (SM), currently performed by the ATC function.

The concept of trajectory-based operations (TBO) claims for a higher degree of integration among safety management layers and the involved actors, promoting a dynamic tasks allocation and continuity between them [4]. TM is still understood as a functional process performed before the aircraft are devoted to delivering the approved flight plans. Whereas SM is understood like all those reactive measures on flights that have to be taken by the ATC, anytime and anywhere the required separation minima is at a risk.

Despite the continuous efforts to improve the safety net coherence, ATC system is heavily dependent upon the human capabilities and some aircraft accidents were characterized by human errors, with underlying failures in the safety management [16]. As a consequence of both the system failures and human errors, the number of accidents had terminated with the fatal outcomes (some of the cases include the 1977 Tenerife runway collision of the Pan AM Boeing 747 and the KLM Boeing 747, which took 583 lives, and the 1996 mid-air collision involving a Saudia 747-100 and Kazakstan Airlines IL76 over Dadri, India, with the loss of 349 lives). With air traffic density increasing, the ATM community has learned both from those accidents and many more occurrences at the "bottom of the accident triangle" (i.e. property accident, severe accident and major injury) - near misses and unreported incidents [17], [18]. This learning process intents to be always driven by the complementary research on the conflict and collision risk assessment through the causal modelling methods and risk mitigation policies [19]. Those methods and policies, however, should count for the trade-off mechanisms between safety, flight efficiency and capacity.

1.1 ATM automation and future operational concepts

In recent years, several important research projects under the Single European Sky ATM Research (SESAR) and the Next Generation Air Transportation System (NextGEN) initiatives, addressing the automation in ATM have been conducted. In [1], automation is envisaged as a process driven by the overall ATM system performance, focused on the system objectives and limitations.

The ATM research on future concepts needs to address all players including flight crews, air traffic controllers and airspace users adequately [20]. Interdependencies between the different stakeholders with non-coordinated decision-making processes are among the crucial elements for the viability of a given concept. A system capability of addressing this type of distributed decision-making needs to meet several requirements in terms of fidelity, operational proficiency and number of participants. The function and task allocations among agents is a key element for a more automated ATM [21]. In terms of automation, the function allocation establishes which agent, human or machine, should conduct the function considering who is better suited for a specific task. From the static to more dynamic approaches, such as the stepwise function allocation models [22], automation is defined in terms of levels indicating to which degree the task should be performed by a human or a machine, considering that any change in the operating mode of air traffic controllers implies transformations in their cognitive associated functions.

Nowadays, the SM function is assigned to ATC, and applied by the controllers issuing separation instructions or directives to the flight crew. This function applies while the situation is considered as an SM issue and assumed that involved aircraft are provided with an advanced look-ahead time (LAT, for instance 5 minutes) before getting into collision, i.e. reaching their closest points of approach (CPA). Thus, involved aircraft have an additional time for separation before being alerted by the TCAS traffic advisory (TA). On the contrary, when a pair of aircraft are close to their CPAs, then the resolution advisories (RA) are triggered one against another, and the crew shall suddenly stop following controllers' instructions and continue with those provided by the TCAS on-board. That involves important operational discontinuities and a very low level of integration between both safety management layers, SM and CA. A similar level of discontinuity and a lack of integration exists between the TM and SM functions. At present, the former only provides the approved or regulated flight plans, known as reference business trajectories (RBT), and:

1. Contains the cleared slot time window for the aircraft to take off (calculated time of take-off),
2. Involves all those management activities producing operational trajectory changes during the flight, driven by both, efficiency and safety targets,
3. Ignores the current or last minute operational state for the available resources [23].

Additionally, for those situations when SM provided by ATC has been unable to provide conflicts removal and a separation infringement occur, the last safety layer towards collision avoidance (CA), exists, which is an independent from the ATC system, airborne-based, and coordinated resource. It is currently developed and executed by the airborne collision avoidance system (ACAS) or TCAS.

On the other hand, International Civil Aviation Organization (ICAO) envisages the airspace user as the pre-determinate separator, unless safety or an ATM design requires a separation provision [24]. This expectation has been foreseen for nominal traffic with lower density. As for the highly dense traffic scenarios, ATC service in the operational context shall be primary provided to airspace users, as controllers are considered the agents with the best information related to the aircraft intents, and environmental and operational conditions.

An increased traffic density, generating a higher complexity in handling the traffic flows, essentially imposes a separation provision to be implemented as cooperative and distributed. In this context, it is necessary to shift from a purely centralized tactical intervention model towards a more efficient strategic planning and more proactive tactical operations, which assumes significant changes of the roles and responsibilities of all involved stakeholders. To this end, a proactive SM is proposed, supported by multi-agent task allocation. The ATC system can be delegated as a priori responsible separator, monitoring and generating a set of safe trajectories for involved aircraft, whereas the decision-making process through negotiation can be assigned among the airspace users. In addition, controllers will support a monitoring mode.

One of the automation-based concepts has been elaborated within the project iFly [25]. The project has been devoted to a highly automated ATM system for the en-route traffic in which a complete concept of operations for autonomous aircraft has been developed. That included the definition of a self-separating airspace (SSA) for autonomous aircraft, where no ATC-separating services were provided. As such, the project has valuably contributed to definition of the aircraft decision-making capabilities as intelligent agents, though identification of the complexity metrics in en-route airspace. The Autonomous Aircraft Advanced (A^3) concept of operations within iFly went beyond what was envisaged by ICAO, NextGEN and SESAR from the operational point of view. The concept assumed that pilots are the only separators from the traffic and other hazards, given the proper infrastructure, equipment and training. It is important to emphasize that A^3 has not considered the mixed operations which include the ATC and airborne self-separated flights.

Several proposals for the future ATM automation have upgraded the roles of air traffic controllers and pilots [26]. For example, under the distributed air/ground traffic management (DAG-TM) [27], [28], pilots would have greater freedom to choose their own heading, altitude, and speed in real time and primary responsibility for maintaining separation from other aircraft in the immediate airspace.

Controllers would not be involved in active control of aircraft but would be in a role of "management by exception" [29], [30]. Management by exception refers to a concept in which managers are notified by staff only if a certain variable exceeds or falls below a certain value. In case of the ATC system, controllers would manage traffic flow, leaving conflict detection and resolution to the pilots and intervene only if aircraft separation falls below a certain value (e.g. 5 nautical miles laterally, and 1000 feet vertically).

The feasibility of DAG-TM concept has been tested in numerous studies with pilots in flight simulations, as in [31], [32]. However, all future concepts envisage a role of the controller to step in and intervene to ensure aircraft separation under certain operational conditions (real-time failure of an aircraft system, weather uncertainty, etc.). It is, therefore, important to examine how well controllers can detect and resolve conflicts when they are removed from the tactical control loop but reentering the loop when necessary to ensure safety.

Collaborative decision-making (CDM) is a concept that goes hand-in-hand with DAG-TM. Under CDM [33], the management of traffic flows and the associated resource allocation decisions are conducted in a way that gives significant decision-making responsibility to the airline operational centers. Under the pre-CDM paradigm, both the ATC and traffic flow management were viewed as a central planning authority with a total responsibility both for the short-term control of an aircraft to insure its safety, and for the longer-term management of flight schedules to insure effective traffic throughput. CDM is based on the principles of information sharing and distributed decision-making. The overall objectives of CDM can be summarized as:

- Generating better information, usually by merging flight data directly from the airspace system with information generated by airspace users.
- Creating common situational awareness by distributing the same information both to traffic flow management and to airspace users.
- Creating tools and procedures that allow airspace users to respond directly to demand-capacity imbalances and to collaborate with traffic flow management in the formulation of the actions.

With the increased transport demand in commercial aviation together with the technological advancements of unmanned aerial vehicles (UAVs) over the last decade, an emerging research challenge recognized in the ATM industry is trying to solve the scalability problems while preserving safety and efficiency [34], [35],. The National Aeronautics and Space Administration (NASA) has envisioned this potential and initiated research into unmanned aerial system (UAS) traffic management (UTM) based on decades of the ATM research and development experience [36]. As the UTM industry with its use cases and technologies is rapidly evolving, the UTM concept and its equivalent in Europe, U-Space [37], consequently evolves. U-Space is a set of new services and specific procedures designed to support safe, efficient and secure access to airspace for large numbers of UAV. The Federal Aviation Administration (FAA) has launched many UAV-related projects to support their future deployment in the civil airspace and integration with commercial aviation. To accommodate the future demand for low-altitude UAV operations [38], previous ATM experiences indicate that this demand must be organized to enable a balance between efficiency and safety. Furthermore, it is necessary to have the systems in place to scale future traffic densities and the mixtures of different UAV types. Accommodating new entrants in a safe manner with the existing airspace users is critical. Hence, at present the main barrier to large-scale UAV operations is the lack of airspace system requirements, procedures, and supporting functions [39].

1.2 Decision support tools

Despite technological advances such as the availability of powerful on-board computers and advanced positioning and navigation systems as, for example, global positioning system and automatic dependent surveillance-Broadcast (ADS-B), the current ATM system is still based on:

- A rigidly structured airspace, the aircraft being forced to fly along predefined routes without the possibility of real-time selection of the optimal routes utilizing , with some exceptions to the flight level allocations in the unsaturated airspaces, where air traffic density is lower [40], [41];
- A centralized, ground-based, human-operated system architecture, the ATC system is responsible for the aircraft separation by issuing the adequate instructions and trajectory specifications to the pilots.

The rapid growth demand in commercial air travel, is putting immense pressure on present ATC system. Controllers can only support a certain number of flights, coexisting simultaneously in a given airspace volume. It should be noted that future traffic scenarios ruled by new cutting-edge procedures such as free flight, advanced ACAS, integration of remotely piloted aircraft (RPAs), or the soft flight level capping constraints are only certain factors that claim for design of the new SM service. Consequently, several proposals have been put forward for modernizing SM to meet the demands for enhanced airspace capacity, efficiency, and safety. According to the SESAR and NextGEN vision, it is necessary to shift from a purely centralized tactical intervention model towards a more efficient strategic planning and more proactive tactical operations, which assumes significant changes of the roles and responsibilities. However, further research on conflict resolution and collision avoidance mechanisms, embedded in the own aircraft equipment and fully addressing the cost-efficiency, safety and security aspects, is required considering the future complex scenarios and the impact of emergent dynamics, that can appear in a particular operational context.

Flight safety is an important problem in civil aviation and flight accidents are the result of multi-elements which affect each other. Safety is typically quantified in terms of numbers of conflicts, i.e., situations where two aircraft come closer than a certain distance from one another. The safety distance is encoded by means of a minimum allowed horizontal separation and a minimum vertical separation. Currently, for en-route airspace the minimum horizontal separation is 5 nautical miles, while the minimum radar separation inside the terminal maneuvering area applies 3 nautical miles. The minimum vertical separation is 2000 feet above the altitude of 29000 feet (FL290), and 1000 feet below FL290. This reduction is known as the reduced vertical separation minima that, therefore, increases the number of aircraft that can safely fly in a particular airspace volume [42].

In order to analyze the aircraft conflicts evolution, from the view of a system safety, the flights can be abstracted to a hybrid dynamic system based on discrete event dynamic system theory [43], [44], and implemented though a systemic causal modelling [45]. In the quest to modernization of the airspace system to reduce congestion and delays, it is essential to develop, deploy, and maintain new decision support systems automation. The goal of such automation is to help controllers manage greater levels of traffic safely, efficiently, and with greater productivity. FAA, with an assistance from NASA, has been successfully deployed the first phase of ATC decision support tools for the autonomous aircraft operations [46]. Although each of these tools provides a valuable benefit to a unique region of airspace (e.g., terminal, en-route) and type of operations (i.e., local control, regional traffic flow management, national traffic flow management, or collaborative decision making), they all share one aspect in common - trajectory modeling. Each tool must generate its advisories based on the prediction and analysis of four-dimensional (4-D) trajectories for each flight operating within its airspace domain [47].

The DST fundamental function is a conflict resolution which is to provide aid in the process of resolving intruder's intent. The review of the conflict detection and resolution (CDR) modeling methods is provided in [48]. Therefore, to prevent conflicts, the ATM system resorts to a two-stage process. In the first stage conflict detection is performed; the positions of the aircraft in the future are predicted based on their current positions and flight plans, and they are compared to detect potential situations of conflict. Once a potential conflict has been detected, the trajectories of the aircraft involved in conflict are planned again in a conflict resolution stage.

When a conflict is detected, a conflict resolution must be provided by the air traffic controller, requesting a maneuver to one of both aircraft, which usually consists of one of three different control actions, summarized below:

- *Flight level change*: One of the aircraft climbs or descents to a different flight level preserving at least 1000 feet at the CPA.
- *Speed change*: By increasing the optimal en-route flight speed by a 6% it is possible to achieve the required safety separation in the horizontal plane.
- *Heading change*: One of the conflicting aircraft changes the original trajectory to a different waypoint to achieve enough distance with respect to the intruder.

The CDR methods are actually given consideration at three different levels of the ATM process, which differ in the time horizon over which a CDR function is performed [49]:

- *Long-term* CDR, is used for airspace planning and management, active at strategic level for the time horizons above 30 minutes. The method focuses rather on the trajectory efficiency than a conflict severity (conflict or collision risk), due to higher uncertainties in the trajectory prediction. The principal objective to implementation is typically air traffic flow management, including the planning of all aircraft trajectories within a relatively longer look-ahead time (LAT), and to maximize the network efficiency and concurrently minimize the ATM operational costs, due to airspace restrictions and requirements such as available capacity at the airports and sectors [50]. Predictions are made from several days up to a 30 minutes before the flight execution [51], [52].

- *Mid-term* CDR, is method applied at a tactical level and updates the prediction time horizon up to 20 minutes. It also presents a planning tool supporting the ATC tasks for the separation management provision with active prediction time of several minutes ahead. Mid-term CDR is intended to support and improve flight guidance from long-term CDR function, with less uncertainties during the flight execution phase. However, uncertainties in the form of trajectory deviations and disturbances still exist, so a sensitivity in the conflict prediction is significantly exposed. With the given LAT, at a certain level of accuracy, the controllers perform a tactical control function of the flight safety. The mid-term CDR tools work in the so-called intent-based mode, trying to identify the aircraft intent based on their state information and airspace system requirements [53]. The LAT for prediction is large enough to allow a tactical control for the flight safety and there is no risk of any potential collision between aircraft [54].
- *Short-term* CDR, works at operational level to avoid the upcoming conflicts, and takes effect horizons up to 2 minutes. With distinction to the long- and mid-term, the short-term CDRs are not planning-based tools meaning that they are counting more for the conflict certainty and safety risk. The optimal and proficient trajectory profiles are not in the scope of managing a short LAT. In general, there are two types of CDR tools implemented. The first is a ground-based safety net intended to assist the controller in preventing conflict/collision between aircraft by issuing, in a timely manner, an alert of a potential or actual infringement of separation minima, known as Short Term Conflict Alert (STCA) [55]. The second one is the ACAS that operates independently from the ground-based ATC system [56].

Another significant difference between the tactical and strategic cases is that measurement and trajectory uncertainties become more important in the strategic case leading to more conservative resolutions (i.e. flow restrictions) which imposes more latent capacity and poor flight efficiency [57]. For tactical cases, both aircraft are more likely to be experiencing the same wind conditions, and the time required to resolve conflicts is small, thus allowing trajectory uncertainties less time to build up. In comparison, the strategic scenario occurs at far range when both aircraft may be experiencing different meteo-conditions and the time for trajectory uncertainties to propagate is much larger.

An important aspect of the transitions between mid-range and short-range CDR methods is the prediction moment, i.e. a time instant at which the loss of separation is anticipated. Time measured from this moment until a moment at which two conflicting aircraft reach their closest point of approach (CPA) is denoted as the look-ahead time (LAT). Depending on the time instant at which a separation minima infringement is predicted, the aircraft states and intents, as well as relative geometries of the trajectories, the CDR function could be properly handled by an ATC directive, such as speed, heading or altitude change. However, change in the active time horizon can introduce the emerging effects and complexity in the CDR implementation due to changes in the airspace volume and surrounding traffic characteristics. [58] reported how major changes in the active aircraft manoeuvrability could potentially induce successive conflicts with neighbouring aircraft and produce a collision effect among them. In these situations, the aircraft separation falls for other safety requirements and is delegated to the safety systems on-board aircraft [59]. TCAS as an airborne autonomous system demonstrates an excellent performance in the pairwise encounters, but suffers from a lack of an extended operational logic due to induced collisions in some complex scenarios, known as downstream effects, or emergent dynamics [60]. To mitigate these effects in a complex multi-aircraft environment, it is essential to develop a future reseach concept towards smooth integration of the diverse DSTs.

1.3 Safety management layers

Safety nets are mechanisms for the prevention of imminent hazardous situations from developing into major incidents or even accidents. In the ATM system, safety nets are intended to provide timely alerts to controllers or pilots of an increased risk to flight safety [61]. The ASM acts as the first safety net, even though it is focused on efficiency rather than safety. In this first stage, a balance between a forecasted demand and an available sector capacity is conducted. The ATM resources are allocated depending on this compromise.

Hours before the flight departure the ATFCM balances the demand and capacity by means of the network manager. The traffic demand is matched with the capacity of each sector, and if the demand exceeds the available capacity and the system is in a maximum deployment state, a sector regulation is issued. An ATFCM regulation limits the number of aircraft crossing an ATC sector, but it does not prevent all conflicts from occurring.

Aircraft is subject to ATC while is flying under instrumental flight rules (IFR). Within an ATC sector, controllers usually perform separation tasks starting roughly from 10 to 6 minutes prior to a potential safety event occurrence [62]. These tasks are considered within the MTCD safety net. For this purpose, the system provides tools in order to predict aircraft trajectories and conflicts among aircraft. However, predictions are not accurate enough and air traffic controllers rely on their experience and skills for performing separation tasks. As aforementioned, an ATC cognitive processes include monitoring the situation, evaluation of the state of different aircraft, formulating solutions and implement the required clearances, among others. The trajectory prediction is based on the known intent of the aircraft and previous experience.

To prevent these situations, STCA seeks for any possible potential or actual infringement of the separation minima among aircraft in the airspace, by means of the projection of future aircraft positions based on the state vector. If so, STCA issues an advisory to the controllers to bring the scenario to their attention. The LAT in the algorithm depends on the adopted standard procedures of air navigation service providers, and it is a trade-off between the nuisance on the alerts presented to controllers, and the actual time which is necessary for solving the scenario. If no corrective actions have been taken by the controllers and the aircraft continue their conflict tracks, the airborne safety net acts. So far, safety nets were part of the SM layer, and pilot had to follow any ATC clearance as soon as possible. If all previous safety nets failed, the CA layer would be the last system resource for avoiding a near mid-air collision.

In near-term operations, the ground-based safety nets are required to work optimally in the future ATM environments. ACAS is globally operable and needs to be optimized and compatible with the existing safety management systems [63]. However, TCAS resolution advisories (RAs) in many cases might be inconsistent with the standard ATC procedures implemented producing a gap in integration of the tactical SM level, with the operational CA level [64]. Therefore, new research lines are required towards development of the collaborative and decentralized SM layer, in which the human behavior and automation will be fully aligned. That anticipates an operational integration of the safety procedures in such a way that any pair of aircraft involved in a potential conflict, together with the surrounding aircraft in a proximate airspace, behave as a stable conflict-free tactical system. Furthermore, the integration should include the critical information on the feasible resolution trajectories generation, included in the development of DSTs.

Potential incoherence between the SM and the CA could occur due to differences between the ATC directive after STCA, and a TCAS advisory. In many complex situations, the ATC system does not timely provide separation services after STCA that activates a TCAS alert. As a TCAS sense is based on a set of logic advisories, considering only nearby airspace volumes, the advisory is frequently opposite from an ATC directive, which is considered from a larger, sector-based volume. This situation may produce an ambiguity in the pilot-in-command decision process, and provoke a higher severity of the conflict event [65]. Moreover, TCAS advisories sometimes require more demanding manoeuvres for the crew, taking into consideration the flight efficiency aspects [66]. Thus, new research concepts relating a coherent integration of the full safety net are essential.

Another main problem is the incompatibility between TCAS and ATC procedures or airspace designs. For instance, when an aircraft is capturing a FL 1000ft above or below a conflicting levelled intruder, it may have as consequence RAs issuances to the levelled traffic. This advisory could arise due to a level bust, for instance. To reduce the frequency of nuisance alerts, mitigation measures have been proposed, such as limiting rate of climb or descent to 1500 feet/minute when aircraft are within 2000ft of the cleared altitudes.

Despite the excellent safety indicators achieved by the present safety net mechanisms, it is recognized that a lack of integration between the different safety layers introduce several penalties in key performance areas such as a latent capacity and an operational efficiency, i.e. delays and maneuvers out of preferred trajectories. Furthermore, the pressure to accommodate more flights to satisfy the increment of air traffic demand, will strain the loose ties between the safety nets with a negative impact on safety indicators. It is notable, for example, that present TCAS II v.7.1, has been designed for operations in the traffic densities of 0.3 aircraft per squared nautical mile (NM^2) [45]. TCAS demonstrates excellent performances in cases of the pairwise encounters but, unfortunately, shows some operational drawbacks in its logic due to well reported induced collisions from specific surrounding traffic (ST) scenarios with higher density [67]. In

[68], there are illustrated several surrounding traffic scenarios in which TCAS resolution advisories (RAs) can induce a conflict.

As a response to the TCAS shortages, the future of airborne collision avoidance lies in ACAS-X [69]. This FAA-funded research and development program of a new CA approach has been active since 2008. The new approach takes advantage of recent advances in computational techniques to generate the optimized RAs. The goal is that ACAS X will eventually replace TCAS as the anticipated benefits will reflect in: reduction of unnecessary advisories in situations where aircraft will remain safely separated; adaptability to future operational concepts that will reduce the spacing between aircraft; extending the collision avoidance to other classes of aircraft that also includes general aviation and unmanned aircraft systems; use of future surveillance environment supported by satellite-based navigation and advanced ADS-B functionality; minimal hardware changes, i.e. ACAS-X will be using the same hardware as the current TCAS as well as the same range of available RAs. However, an improved CA system logic will not facilitate an integration with SM layer as the consistent RAs will still be of a short-time nature.

In summary, the different ATM processes aim at a continuous risk minimization, by means of performing a trade-off between efficiency, capacity and safety of the system, depending on the time to the safety event. When the CPA moment becomes closer, safety becomes the key element for operations. Main safety nets for aircraft encounters with a small time to safety event are the STCA, on ground, and TCAS, on the airborne side. Both STCA and TCAS contribute significantly to the safety enhancement of the system, but there still exist gaps in a coherent transition, necessary to be covered.

1.4 Motivation

An increment in air traffic queries indicates the major concern of how to concurrently accommodate increasing numbers of aircraft in a gradually saturated airspace, while maintaining the required safety indicators. In overall, both the increased capacity and maintained safety are driven towards reduction of the ATC workload and a higher flight efficiency by reduction of the traffic delays. Several attempts have been made in the past, to try resolving the problem. Concepts such as user-preferred routes, autonomous aircraft operations, flexible use of airspace, are the few examples of these attempts. However, the organization of airspace into sectors remains a major constraint to growth in these concepts, since sector capacity is fully dependent on human capacity of solving the complexity induced by large number of aircraft in a given airspace.

1.4.1 Centralized separation management

The decision-making processes, responsibilities, and control in the current air transportation system are set up following a centralized paradigm. In Europe, the central flow management unit assigns slots to aircraft to manage the available capacity of the system, and it de-conflicts high-level request for flights. Airlines schedule their flight and then manage their flight operations from a central unit, where the available flight information is managed and processed to ensure efficient operations and respond to disruptions. The controllers are responsible for the operations of several aircraft at a time in a large area, and pilots must adhere to their directives.

To improve the performance of the centralized control, research activities within the SESAR and NextGEN initiatives aim to introduce automated and decision support systems. These systems either take over or support the control task of the human operator to increase the efficiency and decrease the workload. They can handle higher demand, more complex traffic, and lower margins. As the system state constantly changes automation requires the development of efficient algorithms and provision of sufficient computational resources to compute solutions in real-time. The problem size and computational demand grow with the number of system parameters considered. The human operator is expected to serve as a backup for the automated system, which constrains the allowed complexity of the solutions.

Other research within these initiatives is focused on the restructuring of airspace. Airspace is divided into sectors that are usually each controlled by one air traffic controller. Changing the current airspace layout to increase the number of sectors also increases the number of controllers and the airspace capacity. Currently, the demand varies between sectors, leaving control capacity unused. Dynamically changing the airspace structure would allow making better use of the existing air traffic control capacity. However, the number of sectors is constrained, since aircraft must be handed off between sectors, which causes an additional workload as well.

Since the evolution of the ATM system still mostly relies on the ground-based management and control, it partially limits the airspace capacity. Distribution of SM tasks through different actors can be seen as a solution to the present airspace capacity limits. Thus, the current research efforts are questioning the fixed task allocation on the ground (centric approach), for separation management, and on the airborne autonomous collision avoidance. To this end, a proactive SM system is proposed supported by multi-agent task allocation, where the separation function will be performed by the air traffic controllers, but a cluster of aircraft involved in the safety issue will have an active role in the decision-making resolution process, monitored and supported by the ground-based system.

The centralized separation management represents a controller-oriented separation system generating coordinated resolution advisories that emphasize the system-level stability. In general, the SM performance measures can be characterized by the system stability and efficiency, both locally and system-wide. Locally, SM performance for both arguments are mostly dependent on a controller's workload as well as a traffic scenario complexity [39]. This complexity reflects a traffic density, relative geometries among conflicting trajectories, aircraft states information and intents. The performances at the system-wide level, besides the traffic complexity, depend on the airspace design requirements and the flow management restrictions. The system-level uncertainty is significantly higher comparing to the uncertainty at the local level.

Stability is inversely related to the so-called domino effect, quantified by the number of conflicts induced by the previous conflict resolution manoeuvres. One possible measure of the domino effect is the incremental number of aircraft, flying along their nominally (user-preferred) conflict-free trajectories, that get drawn into conflicts by other aircraft as a consequence of previous resolutions of their own conflicts [70]. System efficiency is inversely related to the system-wide average additional, operational cost of the resulting amendments. In a centralized mode of operations, the focus is typically on maintenance and coordination of a smooth and orderly traffic flow, giving an advantage to stability of the local ATM system for any trajectory modifications.

The common centralized separation strategy applies the constant-speed, heading-change manoeuvres, typically for randomized traffic patterns, encounter geometries at various traffic densities. The results from many empirical studies applying Monte Carlo simulations [71], indicate that both stability and efficiency of the centralized SM degrade with an increment in the traffic density. However, up to a certain density threshold the efficiency could be more perishable comparing to the stability, mostly because of the suppressed effect of the spatiotemporal interdependencies generated by a local traffic characteristics [72].

In current and future systems, the disruptive shift from the ATC instructions to system advisories is not intended to be changed. Although ACAS (or TCAS) system could alert the pilots by means of traffic advisories within a timespan of less than a minute, only when a resolution advisory is triggered the pilots must follow TCAS resolutions. This sudden and disruptive change could lead to significant safety events or even to a mid-air collision.

1.4.2 Operational environment

Based on the current state of the ATM system as well as the communication, navigation and surveillance (CNS) technology, the operational environment is usually evaluated in present or short-term, medium-term and long-term period. In [73], a definition of the operational environment is classified per different ATM categories (Table 1-1, first column). The table illustrates the multi-criteria classification of the ATM operational scenarios [6].

Table 1-1: Classification of the operational scenarios

Scenario	I	IIa	IIb	IIIa	IIIb
Timeframe	Today	Mid-term	Mid-term	Long-term	Long-term
Routings	Classic	Classic	Free-Route	Free-Route	Free-Route
ATC	Sectored	Sectored	Sectored	Sector-less	Sector-less
Trajectory	2,5D	3D	4D	4D	4D
Traffic demand	Actual traffic	Actual +25%	Actual + 25%	Actual + 50%	Actual + 50%
RPA/UAV integration	No	No	Low (3%)	Med (8%)	High (15%)

Nowadays the ATM system is categorized as Scenario I, then a mid-term scenario is introduced as Scenario II in two subsets (IIa and IIb), while the long-term, fully deployed scenario refers to as Scenario III (in two subsets IIIa and IIIb, as well), representing an expected implementation of performance-based operations. The first difference is made in the way the routings are assumed. While today some airspaces have already been converted to free route airspace, there are still conventional airspace routes through several flight information regions. Therefore, for Scenario I classic routing is applied, the mid-term scenario keeps this parameter as a variation between subsets IIa and IIb, while in the long-term subsets automation enables the deployment of performance-based free routing in a flight- and flow-centric ATM. This vision could be materialized either in the form of direct routing or complete free routing airspaces.

Another criterion relates the ATC working strategy. Today ATC is working in sectors, so a defined airspace belongs to one sector, while in future the implementation of a sector-less ATM might come into place, where one controller might be responsible for a number of the whole flight envelopes instead of trajectory segments within a sector [74].

The current flight plans can be understood as the 2.5-D trajectories, since their currently used format does not allow precise transfer of information from the airline operations center to ATC. In the future, this will be changed to more precise data initially delivered but monitored and reached agreements during a flight in a form where they adhere to expected 4-D trajectory standards. This will only be the case in the IIb mid-term and the long-term scenarios. It is assumed that for mid- and long-term scenarios, the sharing of information across system wide information management will allow maintaining fully updated trajectories, for the airborne and ground subsystems, as well as a higher adherence level to an agreed reference trajectory.

TBOs foresee sharing of the same information via datalink communications between the airborne and ground subsystems throughout the business trajectory lifecycle. Thanks to TBOs, the flight- and flow-centric operations have been gradually evolving into more advanced concepts of operation, such as free route operations. This has enabled airspace users to fly their preferred trajectory satisfying their business needs, and to perform continuous descents and climbs generating environmental benefits both in terms of emissions and noise. An airspace configuration will be dynamically adjusted in response to capacity and demand needs [75]. The flight- and flow-centric operations in a network context will see the introduction of the complexity tools to enable air traffic controllers to work on flows rather than individual flights. This will allow flexible and optimal use of controller resources, thereby generating gradual changes in their workload and cost efficiency [76].

In addition, it is expected an initial integration of remotely piloted aircraft (RPA) and UAVs into civil airspace. As a starting point, they might only be integrated with a lower priority, or allowed in a certain airspace, and this is expected as a variation of scenario IIb. In the long-term IIIa, it is possible to see them as even users of the airspace, so their presence might reach or replace the manned aircraft, at least in certain areas. Therefore, in the long term the variation in the number of operations might the priority subject related to the business preferences of the operators. The integration of all unmanned vehicles is one of the requirements for an achievement of the performance targets within the European ATM system.

1.5 State of the art

1.5.1 Decentralized separation management

Another approach to increasing the available capacity of the central resources in the air transportation system is to reduce the number of tasks that controllers perform, by decentralization of the SM decision-making processes. In this specific context, decentralization is the process of moving decision authority, responsibility, and control away from centralized resources to distributed entities in the System. Example projects that embrace the benefits of decentralization are *free flight*, where aircraft determine their flight trajectory themselves, and *self-separation*, where aircraft ensure safe separations with other aircraft themselves. Decentralization of some of the tasks that are performed at the coordination resource would free up capacity to perform other tasks that can only be performed centrally.

While the air transportation system is commonly modeled and addressed as a centralized network, fragmented processes govern the actual performance and operations. Note, for example, that pilots are subject to their local conditions when deciding how to respond to a command given by air traffic control. The air traffic controller cannot directly influence the trajectory of an aircraft. As a flight is getting ready for take-off, several local processes, such as baggage and passenger loading, maintenance, and fueling have to be completed.

Each of these processes can contribute to disruptions and delays on the ground. The progress of a flight in the air is impacted by local conditions such as aircraft performance, weather, and other traffic. The large number of these local processes and their interactions leads to a very high system complexity, which can be difficult to capture and respond to by centralized coordination. The motivation to move away from a strictly centralized paradigm and seek decentralized control in the air transportation system is two-fold:

1. Implementing decentralized control reduces the number of tasks that are allocated to a centralized control unit. Decentralized control has an access and a capacity to take local information into account in their decisions. The capacity of a decentralized system increases as the system grows.
2. New distributed systems are being developed that challenge the centralized paradigm. Free flight' and self-separation are proposed concepts for the future operations. RPAs that aim to become an integral part of the transportation infrastructure could be operated in a dedicated airspace outside the ATC supervision and responsibility.

The conventional management schemes are being replaced by extensively integrated management systems to maintain safety levels and increase throughput of congested airspaces. On the other hand, present aircraft control, communication and navigation systems allow increasingly complex decisions to be taken on-board, thus enabling a progressive move towards decentralized control scenarios, supported by the airborne separation assurance system [77], [78].

When considering decentralized control scenarios, a method for decentralized separation management or conflict resolution includes, in general, four properties [79]. First, the conflict resolution is *distributed* such that pairs of aircraft determine their own conflict resolutions, without relying on a centralized mechanism to resolve the conflict for them. Theoretically, this property provides an efficient parallel mechanism to obtain local optimal solutions of a large-scale optimization problem. Application-wise, this mechanism increases the efficiency of autonomy in terms of smaller delay time, as well as the efficiency of the traffic in terms of larger throughput in the absence of ATC to mediate the conflicts [80].

Second, the simultaneous maneuvers by both aircraft are negotiated between the two aircraft so that they jointly establish a successful conflict resolution. Thus, unlike methods that only provide a maneuver to one aircraft, or negotiate which one aircraft will maneuver, the maneuvers are coordinated between the aircraft. This typically results in each aircraft's maneuver being significantly smaller than if only one aircraft maneuvers, with a corresponding reduction in total cost.

Third, the conflict resolution is not only distributed, but also decentralized. While the terms distributed and decentralized are often used inter-changeably, decentralized operations are distinguished as the further special case where the individual agents (aircraft) while interacting try to impose their business preferences in terms of the operational feasibility and optimality. In conflict resolution, such private information specifically includes the airspace users' cost indexes (weighting the relative costs of fuel burn and delay incurred by the resolution) and other business decisions that impact performance constraints.

Finally, the decentralized conflict resolution is multi-dimensional. At each discrete time instant the solution characterizes the combinations of the coordinated or non-coordinated resolution maneuvers: climb/descent, right heading/left heading, and speed up/slow down. Each of these resolutions are negotiated such that the lowest cost dimension for resolving the conflict could be selected. This formulation also accommodates constraints on maneuvering in specific dimensions due to aircraft performance constraints (e.g., limits on speed or altitude) and other constraints such as restricted airspace.

The decentralized SM represents a user-oriented separation system generating independent resolution advisories that emphasize aircraft-level efficiency [81]. As in case of the centralized separation function, the results from numerical experiments indicate that both stability and efficiency degrade as traffic density increases. In light of the advanced CNS technological enablers, such as ADS-B, and a limitation of the controllers' workload, decentralized separation strategies could more effectively mitigate the domino effects locally (i.e. the surrounding traffic in a proximate airspace). Thus, for local traffic densities up to a certain threshold, the stability level in providing the resolutions might be maintained while the resulting drop in system efficiency could be quite small. However, with an increased density the scalability effects impose a negative quantification of efficiency [82].

System efficiency is inversely related to deviations from the nominal (i.e. user-preferred) trajectories. Moreover, under conditions of high traffic density, it is conceivable that the underlying efficiency of decentralized operations may be negated by the frequent trajectory interruptions for separation assurance. As in case of the centralized separation management (refer to section 1.4.1), the decentralized separation management usually applies the constant-speed, heading-change maneuvers strategy, mostly for cooperative flights.

To address these drawbacks in present and future air traffic, further research in the ATM safety is required towards development of a collaborative, proactive and decentralized SM system considering a socio-technical approach in which both human behaviour and automation will play an important role [83], [84].

1.5.2 Causal spatiotemporal interdependencies

As elaborated in [85], causal models for an aircraft risk and safety assessment of the ATM operations establish the theoretical framework of causes that might lead to aircraft accidents. They can be qualitative or quantitative. The former provides a diagrammatic or hierarchical description of the factors that might cause accidents, which is useful for improving understanding of causes of the accidents and proposing means for avoiding them. The latter estimate the probability of occurrence of each cause and thus estimate the risk of accident. This can be restricted to pure statistical analysis based on the available data, or it can combine such data with an expert judgement on the causes. In addition, they can estimate the relative benefits of different interventions aimed at preventing the accidents [86].

The causal models include the following three types: sequential, epidemiological and systemic accident model [87]. In the systemic accident model, an accident is regarded as not only a cause-effect mechanism, but also more of a system chaos/emergence that results from the interactions between the system components. Because this model is not limited to a fixed cause-effect relationship, it can dynamically describe the non-linear development process of the accident.

An increased interest in the causal models has mainly been arised for:

1. Better understanding of effects of different influencing factors on a level of risk;
2. Evaluation of an overall risk, a risk communication, and a cost-benefit analysis of new technologies;
3. A training of the aviation staff and identification of the system components that could be improved;
4. Identifying critical causes of the aircraft accident as well as measures for reducing the risk. In order to decide which measures for risk reduction should be adopted, regulators and safety managers need to understand the causes of accidents and be able to evaluate benefits from various interventions [88].

The provision of coordinated and compatible trajectories among for all involved aircraft in a potential multiple safety event is supported by the causal DSTs. A design of those tools requires a careful identification of all neighboring aircraft involved, and their downward connections. The introduction of higher degrees of autonomy and the inclusion of identified aircraft in the decision-making process for solving the conflict scenario could be seen as if clusters were composed by the living organisms.

In general, an ecosystem is defined as the complex of living organisms, their physical environment, and all their interrelationships in a particular unit of space [89]. It can be drawn an analogy to any scenario in which a set of aircraft within a cluster (as a spatiotemporal proximate airspace volume), placed in an operational and physical environment, has the pairwise interrelationships, for an assurance of a safe and efficient conduction of all operations.

The proposed concept of aerial ecosystems – a tactical air traffic system - presents a new operational framework that intends to solve the time horizon paradigm in a multiple aircraft environment. The principal function is to identify the system causality and decrease a solution complexity at the SM level, not triggering the TCAS alerts for any potential state and intent change. An ecosystem can be described as a set of aircraft with the trajectory-amendment and decision-making attributes, whose trajectories are identified inside a computed airspace volume (i.e. cluster) and are causally involved in a safety event through identification of the spatiotemporal interdependencies (STIs). The concept relies on a quantitative analysis of STIs between aircraft positioned in a computed airspace volume, formed proximately around a detected pairwise conflict that will fairly 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 operationally predict a surrounding traffic emergent behaviour and identify a subset of trajectory amendments, that will not cause a negative domino effect with the neighbouring aircraft [54]. Figure 1-1, for instance, depicts how a negative domino effect might appear in an atypical collision avoidance scenario with four aircraft, in which the successive TCAS alerts are fired as consequence of the previous collision avoidance maneuvers (TCAS RAs).

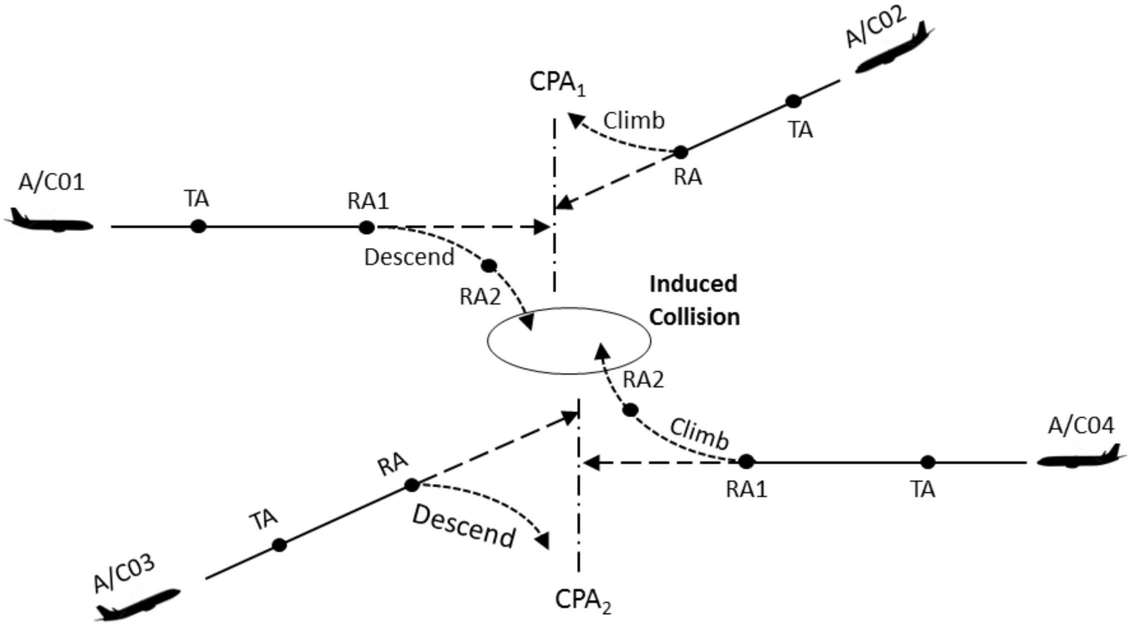

Figure 1-1: Induced collision avoidance scenario [68]

As the CA layer activates in less 60 seconds before CPA (subject to the aircraft dynamics and intent), once resolved conflicts produce very high uncertainty in guidance over the amending RBTs. After its amendment, A/C01 generates a new collision with A/C04, denoted as an induced collision. It is characterized by an instantaneous RA alert, while the aircraft is still performing requested resolution maneuver and not resuming to its RBT.

Therefore, an STI exploration could be done timely, in advance, by applying the proper functional metrics at the certain timestamps, preceding the conflict event. This position should guarantee the coherence between the SM and CA layers and the functionalities before and after the STCA threshold. In [90], it is shown that the earlier in advance of a predicted conflict the resolution manoeuvres are considered, the smaller will be the probability in violating the separation minima with the neighbouring aircraft.

A quantitative approach could be deployed for analysis of the ecosystem complexity considering the aircraft interdependencies, that might arise due to performed resolution maneuvers. A state space exploration as approach supports a system-level search for all states from interdependencies, in which the aircraft could reach a final one as conflicting, called an ecosystem deadlock event [91]. This event is characterized by a time instant at which an induced collision could emerge as an effect of previously applied maneuvers. The deadlock depends on a relative geometry of the ecosystem trajectories, the aircraft closure rates and performances. A full understanding of the emergent dynamics, together with the effects of uncertainties and perturbations on the traffic behavior is a mandatory for expected research achievement in development of the multi-aircraft conflict management framework.

1.5.3 Multi-agent system in ATM

There is abundant literature in the use of the multi-agent system (MAS) for problem solving of complex system behavior [92], [93]. However, a word of caution should be considered in the deployment of MAS applications for CR due to criticality of the spatiotemporal interdependencies present in any specific airspace volume configuration, which could generate so many different emergent dynamics, each one requiring certain resolution trajectories to avoid new downstream conflicts. Thus, there are some CR applications with excellent results when applied to *miles-in-trails* traffic scenarios [94], in which traffic is structured into flows of aircraft, following the same path, and the crossing waypoints are in the 90°-intersections between the trajectory profiles. Thus, MAS verification and validation described in [95] becomes a hard requirement for realistic scenarios when modelling a conflict management system, especially due to a set of the following attributes:

- *Correctness*: The system should be 100% correct, so resolution trajectories should be consistent with aircraft performance and weather conditions;
- *Usability*: The system should meet users' demands and preferences, as well as ATM constraints.
- *Reliability*: How often the system fails to arrive at the correct maneuver resolution.
- *Competency*: The quality of the knowledge in a system relative to human skills.
- *Testability*: The system must be designed in such a way to permit a testing plan to be carried out.
- *Adaptability*: How closely the system is tied to a single model of work.
- *Consistency*: The requirement specification or system is free of internal contradiction.
- *Completeness*: Is a measure of the portion of specification implemented in the system.

The last three attributes are the key ones and usually can only be successfully achieved for a reduced set of conflict scenarios in which the operational context is under control. Thus, there are some CR applications with excellent results when applied to *miles-in-trails* traffic scenarios [94], in which traffic is structured into flows of aircraft, following the same path, and the crossing waypoints are in the 90°-intersections between the trajectory profiles.

As for realistic scenarios in which tight interdependencies between aircraft trajectories in a saturated airspace volume can easily generate emergent dynamics evolving towards new unexpected situations, the last three MAS attributes are considered important due to the difficulties to replicate present system behavior:

- *Adaptability*: It is well accepted that ATC have different work models switching from one to another according to the predicted workload. Thus, when a peak workload is predicted, ATC use to issue more conservative directives (heading away the aircraft) which affects negatively some key performance indicators but avoid the ATC time-consuming monitoring task and issue more directives to the same flight.
- *Consistency*: Rules used for agent behavior specification sometimes are in contradiction since some ATM performance KPIs are also contradictory. It is well accepted that airspace capacity is somehow in dispute with safety.
- *Completeness*: Models are a formal specification of the system dynamics under study for a certain context which usually is described by means of hypothesis and boundary conditions. To satisfy CR completeness MAS requirement, usually the MAS model is formulated only for a very restrictive scenario solving concise traffic problems.

A full understanding of the emergent dynamics, together with the effects of uncertainties and perturbations on the traffic behavior is a must to really succeed with a MAS CR framework. An alternative to MAS that can support emergent dynamics is the agent-based modeling system (ABMS) approach. The main difference between the two, is that ABMS focuses on the collective behavior of agents, instead of using agents for solving specific practical or engineering problems. Thus, ABMS framework can reveal system behavior emerging from the agents' collective actions and interactions. Several ABMS applications can be found in the literature [96], [97], but the completeness requirements cannot be fully guaranteed when simulating a realistic air traffic scenario. Some alternatives that try to enhance ABMS with the completeness requirements rely on a stochastic analysis using Monte Carlo simulations [98], and sensitivity analysis for dealing with the inherent ATM uncertainties. Unfortunately, completeness cannot be accomplished with Monte Carlo simulation. In [45], it is shown how very rare events which appear only under specific traffic conditions for particular time stamps can provoke a TCAS failure, with a very low coincidence probability that could be identified using stochastic simulation methods.

Figure 1-2 illustrates an adaptive, self-governed, aerial MAS. Four agents, equipped by an enhanced TCAS capability (E-TCAS) and involved in safety event – detected conflict – actively interact for the resolutions agreement. Figure 1-3 describes the time horizon problem in the negotiated MAS framework when the resolutions capacity (i.e. number of the system solutions) decreases over time, as a penalty for any missed resolution decision.

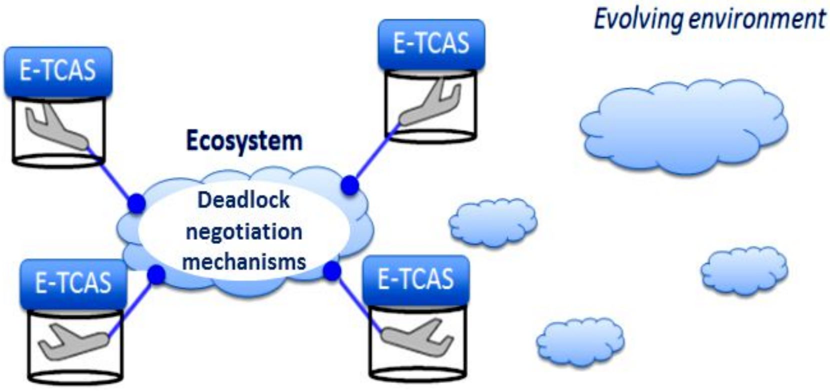

Figure 1-2: Ecosystem as a multi-agent system with all three elements: aircraft agents, negotiation interactions for resolutions and evolving environment

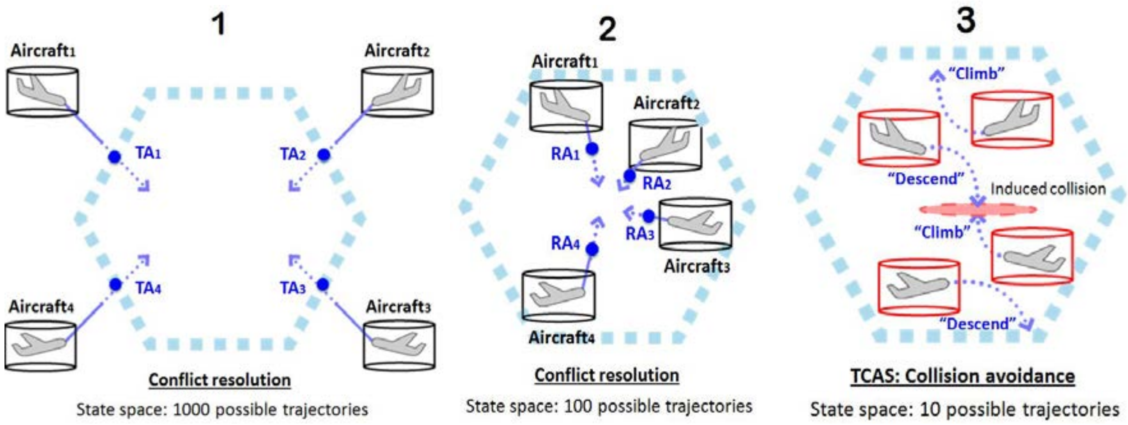

Figure 1-3: Negotiated MAS implementation in the safety-critical application (CDR for an ecosystem of aircraft)

Being in a system where each agent (in our case aircraft) seeks to maximize its own profit, makes it impossible to define a unique optimum for the whole system. This is a well-known restriction which lies in the foundations of game theory [99]. Several solution concepts are proposed in literature, each one having its pros and cons. Among them the two most well-known ones are Nash equilibrium and Pareto optimum [100].

Nash equilibrium defines a sense of rationality by having the property of being the best individual choice given the actual choices of the other agents. Pareto optimum is a solution where no agent can do better without "hurting" any other agent. Both solution concepts have a wide area of applications, however none of them is fully applicable to the case above (Figures 1 and 2). The problem with Nash equilibrium is that quite often it is Pareto-dominated, i.e. there exists another solution which is better for at least one of the aircraft and as good as the equilibrium for the rest. Being in a collaborative environment, makes this situation not desirable. The problem with Pareto optimum is that, over time it can be quite bad individually. In a situation with five aircraft for example, a proposed solution which is a Pareto efficient can be unacceptable for some of the aircraft.

In these conditions a hybrid solution concept, that of satisficing [101], is the best alternative. Under this concept each agent needs to give its minimal requirements. The goodness and acceptability of solutions is defined based on the aggregation of these requirements. Satisficing comes with several advantages, two of which are mentioned here. Firstly, it engages the agents in the decision making, which in previously described context means the airlines are getting engaged, therefore the decision-making is distributed.

To state the second advantage the problem needs to be considered as a search problem[1]. In doing so, the process of finding a solution would be equivalent to defining a search strategy. Search strategies can

[1] Searching for conflict-free configurations of the system in the domain of possible configurations.

be classified to exploratory ones, in which the leading principle is to explore the search space as broadly as possible and exploitative ones, in which the leading principle is to find a solution as soon as possible [102]. It is clear, that exploitative strategies converge faster. One of the implications of choosing the satisficing as a solution makes the system free of local optima[2]. Considering these two observations, exploitative search strategies, which means faster convergence to a solution, are the considerable ones.

1.6 Objectives

The doctoral dissertation implements an SM framework relying on the concept of aerial ecosystems to transform divergent targets between separation management at the tactical level and collision avoidance algorithm at the operational level, into a cooperative efficient conflict-free traffic system. 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 among the ecosystem aircraft and its ever-changing environment. Developed framework is underpinned by the quantitative methods and metrics in identification of the spatiotemporal interdependencies as the means of computation of a number of the ecosystem solutions. The research formalized through this dissertation elaborates the ecosystem identification model equally applicable to both ATM and UTM. The following objectives are summarized as follows.

- Determining the traffic complexity taking into consideration the so-called domino effect, i.e. the number of the surrounding aircraft causally involved in the separation management service of two aircraft by the means of identification of the spatiotemporal interdependencies among them.
- Integrating the separation management with collision avoidance layer through computation of the ecosystem deadlock event, as a moment in which the number of the ecosystem resolutions reaches zero value.
- Providing the sensitivity analysis of the conflict-free solutions for the cluster-ecosystem ratio. The computational procedure is based on the stepwise simulations of the cluster–ecosystem transitions using different identification parameters.
- Testing and implementing the conflict management to the unmanned aerial vehicles, focusing on the application of smart vehicle connectivity technologies for the identification of the spatiotemporal interdependencies among them.

1.7 Document structure and context

The research aim of this doctoral dissertation is a causal analysis and simulation of the tactical, multi-aircraft conflict management framework, formalized throughout the concept of aerial ecosystems. The research scope includes the quantitative methods for identification of the spatiotemporal interdependencies and computation of the total system-level solutions and deadlock within available operational time. The dissertation comprises several analytical outcomes utilized by the means of configurable metrics and performance parameters and tested on various traffic scenarios. Finally, the framework has been initially utilized in the field of UAVs by initial testing of the ecosystem missions. The list of the outcomes is depicted in Figure 1-4.

[2] Definition of optimality in the multi-agent environment is not clear, neither straightforward, but the reader can understand the analogy.

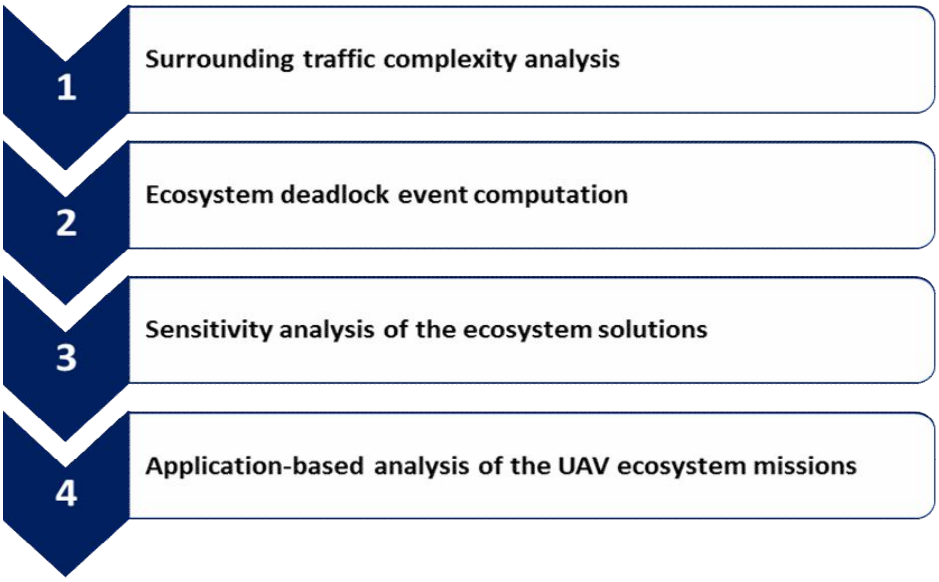

Figure 1-4: Depiction of the research outcomes

1. An analysis of surrounding traffic complexity (Chapter 3). This complexity metric is driven by the interdependencies structure and expressed as a time-criticality in quantifying the resolutions capacity, that could be affected by changes in the number of surrounding aircraft and relative geometry of the ecosystem trajectories.
2. A computation of the ecosystem deadlock event (Chapter 4). The computation considers the following aspects: cooperative mechanism (i.e. all ecosystem aircraft in the resolution amendment initialize the maneuvers at the same time instant); the resolution maneuvers correspond to the avoidance maneuvers with a certain discretization of the heading and vertical rate; the resolution maneuvers are considered potential as some of them might be acceptable and other unacceptable by the airspace users.
3. A sensitivity analysis of the ecosystem solutions for the cluster-ecosystem ratio (Appendix A). The sensitivity in this study denotes a comparable distinction between the simulated ecosystem scenarios, meaning that a small distinction among the ecosystem solutions denotes a higher sensitivity value.
4. An application-based analysis of the UAV ecosystem missions (Appendix B). The analysis is driven by consideration of the scalability problems in the highly dense operational scenarios. This objective is to justify the applied separation criteria among small, cooperative unmanned aerial vehicles based on their performance characteristics and planned mission types.

Chapter 2 introduces the aerial ecosystem concept though developed stepwise algorithms. It describes the conflict management framework by the means of the modeling methods, assumptions and criteria. A special attention is given to the STI quantification.

Chapter 3 presents the paper entitled “Surrounding traffic complexity analysis for efficient and stable conflict resolution”, which has been published in the Transportation Research Part C: Emerging Technologies (2018, 95: 105-124). This paper considers a baseline of the STI identification with the surrounding traffic as a complexity metric, expressing the structure of the conflict intervals as a combination of the potential conflict maneuvers. The model has an ability to further explore the potential ecosystem resolution capacity in the search space of the system solutions. The analytical method is applications-oriented rather than a theory-based, developed with a quantitative and less conservative modelling approach, and customized to the current traffic demand and the operational environment. A decreasing rate of the available ecosystem resources and an elapsed time describe a potential path in a thorough analysis of resolution dynamics, meaning that each missed moment in making a resolution agreement might induce less number of the conflict-free maneuvers, but also maintain or increase them in some circumstances. The factors, like a relative geometry between trajectories, closure rates, flight modes and conflict types influence the changes in the interdependencies structure over time.

Chapter 4 illustrates the manuscript “Adaptive aerial ecosystem framework to support tactical conflict resolution” that has been published in The Aeronautical Journal (2018, Vol/Issue: 1-19 – PRESS). This article aims at improving the quantitative computation of a decreasing rate in the amount of potential ecosystem solutions as well as the ecosystem deadlock event in which this amount reaches zero value, meaning that at least one ecosystem aircraft cannot perform any conflict-free maneuver that will remove a collision avoidance state and potential TCAS advisory. The approach has shown a significance in providing the time capacity for a set of certain maneuvers at the operational level, when a severity of the conflict situation occurs very rapidly. Simulating diverse traffic scenarios, the computational framework can illustrate the cases of a variable resolution capacity that decreases over time at a different rate. With an increased ecosystem size (i.e. number of involved aircraft) and diverse trajectory geometries, the STI structure becomes larger which produces less resolution capacity and a shorter ecosystem time.

Finally, Chapter 5 contains the overall conclusions and future work.

In addition, the thesis comprises two appendices. Appendix A introduces the work entitled as "Sensitivity Analysis of Conflict-Free Resolutions for the Airborne Cluster-Ecosystem" which has been published in the Journal of Air Transportation (2018, 26(1): 37-48). The sensitivity analysis was performed by the initialization of different cluster–ecosystem transitions with the goal of measuring the scenarios complexity in terms of the time-based conflict-free solutions, in front of the elapsed time to the aircraft collision. A difference in the transitions are obtained though testing of different cluster and ecosystem parametric values (refer to Chapter 2). Sensitivity in the paper denotes a comparable distinction between different simulated ecosystem scenarios. Higher sensitivity means smaller distinction and vice versa. For the same ecosystem size and slight difference in the geometry of the ecosystem trajectories, the sensitivity might be significant that consequently affects the ecosystem resolution capacity over time. The analysis provides an insight on a potential deployment of aircraft negotiations as their tendency to reach a resolution agreement via early or late decisions.

Appendix B describes the article "Scalable Conflict Management Framework for Air Transportation" that is currently under review in the Journal of Advanced Transportation. The article elaborates the conflict management framework applied to UAVs, focusing on the application of smart vehicle connectivity technologies for the STI identification between UAV missions. The work considers the future scalability problems in the high dense scenarios. It is seeking for a justification of the applied separation criteria among small cooperative UAVs treating them as a conflict mission system, that strives to achieve an efficient solution by applying certain maneuvering measures before a loss of separation occurs based on their performance characteristics and the planned mission types. The adopted criteria present the testing asset, referring to a current lack of spatiotemporal requirements and a need for performing more research in this area to provide a more rapid integration of these vehicles for passenger and freight transport purposes into the civil airspace.

2. Ecosystem framework

Nowadays there is no rigorous tool to analyze the induced conflict/collision, to test the TCAS multi-threat logic, and to identify all the failing scenarios that should be avoided in advance. Taking the future unsegregated airspace as an example, it would be possible to have a situation in which improper maneuvers that were issued by TCAS to resolve one-on-one encounters between manned aircraft induce a collision with a secondary threat that appears to be a domino effect (i.e. emergent dynamics) to the neighboring aircraft of previous decisions. By enhancing TCAS range and extending functionalities, ATC workload could be lessened while increasing pressure on pilots, which could degenerate to a saturation of the sensorial channels. It is well accepted that ATC change their control mode towards more conservative rules when the coexistence of mental tasks is nearby a threshold, however there is no evidence that pilots could change their mode in some dense scenarios under the pressure of receiving different traffic and resolution advisories.

One of the visions for the future viable ATM system is addressed in the exploratory research project AGENT, that proposes the development of an adaptive self-governed aerial ecosystem by negotiated traffic. The project deploys the mechanisms and tools for induced conflict avoidance while dynamically creating temporal virtual ecosystems of aircraft as soon as a conflict is anticipated (considering uncertainties) providing different negotiation-based resolutions both at the conflict resolution and collision avoidance levels accounting for safety, security, capacity and cost-efficiency aspects.

Therefore, AGENT seeks to implement a new framework extending the functionalities of TCAS to act at pre-operational (i.e. tactical) and at operational level as a robust conflict management system for different contextual scenarios in which human behavior, automation-based interdependencies have been considered with the realistic aircraft performances. The principal idea is to technologically support an irruptive shift from a nowadays centrally controlled ATM system to a distributed system, in which all aircraft are enhanced with smart cooperative and competitive DSTs to fly their optimal routes (i.e. direct routing), and the task of traffic separation is moved from ATC to the cockpit (i.e. airborne separation).

The key areas for AGENT that have been identified are:

- Complexity of scenarios and ecosystems;
- Agility, stability and flexibility of the process;
- Quality and computation effort of provided solutions;
- Necessary expansion and sensitivity of AGENT to external influence;
- Technical parameters of the ground and airborne subsystems.

2.1 Concept of operations

The ecosystem identification is conducted in a stepwise approach. First, space-time traffic filtering is performed for analyzing of potential pairwise conflicts, or STI metrics above a certain threshold, among a larger number of aircraft. This process is generally considered as a hotspot creation. Second, once traffic hotspots have been generated, clusters are created within hotspots, around detected conflicts, as a spatial category. Both hotspots and clusters are dynamical categories in terms of the number of aircraft. It means, for instance, that one cluster could cover a monitoring process of two or more aircraft taking into consideration their flight intents in larger time horizon (up to ten minutes). As a result, it can evolve into ecosystem if the trajectory interdependencies detect a conflict event within LAT, with respect to CPA.

An ecosystem as a multi-agent system considers both the involved aircraft and ATC as intelligent agents for the right decision-making, in which the number of aircraft starts with the principal case of a pair-wise conflict but without limitation in a scenario extension, as the number of aircraft depends on the traffic configuration and the complexity in establishing the ecosystem structure.

Based on the potential of a machine-to-machine communication as the means of the agents' negotiation interactions, the ecosystem concept can prevent from the TCAS failure scenarios due to multi-thread conflicts and induced collisions by a conflict-free state space exploration and monitoring of surrounding traffic, enhancing the TCAS range. The integration of SM and CA nets within an ecosystem would require DSTs with the ability to send and receive both current state and intent information [25], as:

- Cockpit display of traffic information for situational awareness;
- Autonomous conflict detection and prediction;
- Ground-based traffic monitoring;
- Coordinated conflict resolution for all aircraft members of the cluster.

The ecosystem functions are collaboratively performed by the ATC and involved aircraft (agents), although ATC is always considered the main separator. ATC ground tools conduct the synchronization and updates of the trajectories, the evaluation of the ecosystem state and generation of the potential resolutions. On the other hand, aircraft will negotiate to find a commonly agreed conflict-free solution for all members while the ATC will monitor the negotiation evolution to be ready for a potential deadlock. In case the negotiation is near to reach a deadlock state, or the evolution of the members is compromising the safety of the operations, ATC imposes a compulsory combination of resolutions for all agents. The decision to issue the compulsory resolutions depends on two states:

1. The ecosystem has closely approached the deadlock state;
2. The ecosystem state has evolved towards a complex scenario in which safety is potentially compromised. For a pairwise conflict, as the minimum representation of an ecosystem, it would be given a time limit of 50-60 seconds before the CPA moment (depending on the closure rates and flight configurations, but before entering the CA layer) for the compulsory resolutions. For ecosystems involving more aircraft, it is likely that it would be triggered sooner (for instance, at the STCA alert, 90 – 120 seconds before the CPA moment, or even before this alert), as complexity is foreseen to increase with the larger number of ecosystem aircraft.

Finally, the negotiation process among aircraft and ATC seeks for an agreed solution for all agents depending on their different business models. For agents, the most predominant metrics will be the fuel consumption and the time-cost efficiency, meanwhile for the ATC, safety and the agents' compliance to RBTs are the principal elements for consideration, keeping in mind the impact on safety of the local operations or on the predictability of the system. Therefore, negotiation interactions within the ecosystem are allowed until negotiation positions are static and do not evolve towards an agreed solution, or the safety is compromised based on complexity considerations.

2.2 Ecosystem processes

The ecosystem creation is envisaged as a stepwise process, in which successive steps allow the transition from traffic filtering to ecosystem identification. The main driver for both the clusters and ecosystems formation is based on the STI determination. To do so, two approaches could be followed:

1. Conflict detection and membership identification, with different look ahead times and thresholds depending on the entity created (cluster or ecosystem) [103];
2. Specific metrics for the STI determination among aircraft. Each entity has its own LAT and metric threshold for triggering its creation [104].

In former, the conflict detection function detects two aircraft which potentially can be involved in a safety event. Once this pair is identified, an expansion process based on a state space analysis with the rest of surrounding aircraft will determine the size and members of the entity. In latter, the process evaluates the STI metric and determine the members of the entity and its creation.

Once created, the ATC system continuously evaluates the ecosystem state, performing the tracking function. Primarily, the tracking is supporting on a continuous counting of the total number of solutions over time for the ecosystem members. Secondly, the agents in parallel interact among themselves for reaching an agreed solution. The generation of resolution trajectories is based on the state space exploration supported by a quantitative method for discrete aircraft maneuverability within LAT of 300 seconds. This generation is a centralized process, which afterwards is communicated to the members.

In theory, it can be noted that the set of compatible resolution maneuvers is constantly reduced with the time evolution due to the perishable characteristic of the maneuvers quantity while the ecosystem member states are evolving during negotiations. Figure 2-1 illustrates a theoretical case of the perishable speed of resolution maneuvers considering two traffic scenarios. Thus, the perishable speed in a complex traffic shall promptly deal with shorter time to a deadlock, while in a weak surrounding traffic scenario (ecosystems with 2 or 3 members) the perishable rate is lower. Consequently, for complex traffic scenarios compulsory trajectories must be triggered sooner than for weak scenarios as the elapsing time to deadlock is shorter. Nevertheless, the analytical expressions for counting a cumulative number of the ecosystem solutions over time has been elaborated (refer to Chapters 3 and 4).

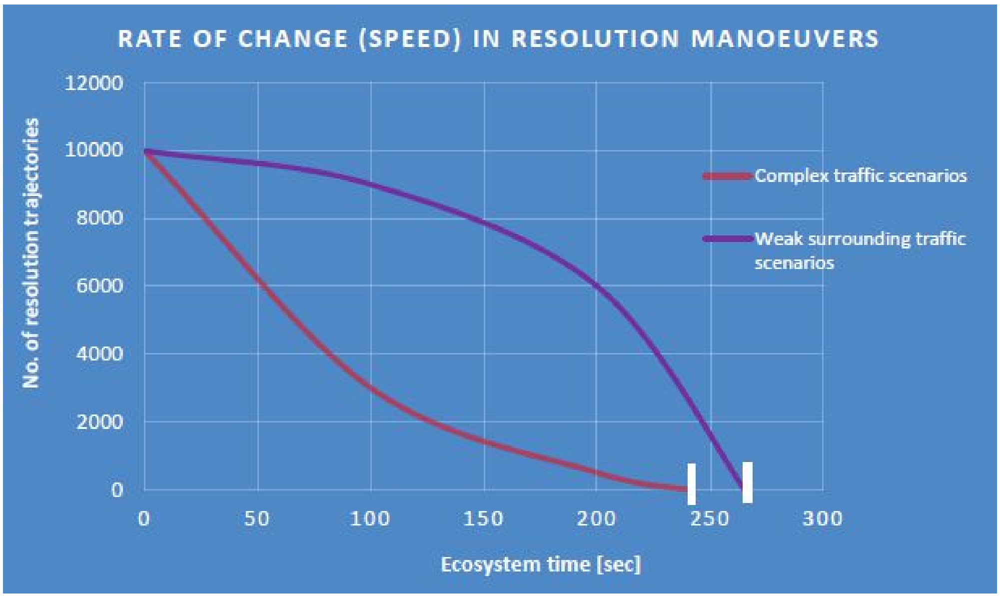

Figure 2-1: Perishable rate in the number of resolution maneuvers for two scenario types

Once the concept of resolution maneuver is defined, the concept of its weight needs to be introduced. The weight of a determined maneuver is defined as the number of real (or, feasible) maneuvers it provides to the combination *S* of total resolution maneuvers. This second concept is introduced as intends to emphasize the fact the more time measure moves forward, the less space for real maneuvers there exists. It is defined the work hypothesis that has been imposed to calculate *S* (*t*) as follows:

- α is fixed as the maximum acceptable heading change for both the left and right turns. α by defaults my also denote a gradient for a vertical rate change, referring to the climb or descent operation.
- The weight of a solution is directly proportional to the distance *r*. Where *r* is the opposed cachets to the triangle rectangle, which is defined between the prefixed trajectory of the aircraft and a hypothetical of such that would be initialized when performing a maneuver with angle α. Figure 2-2 displays how the range of possible real solutions (determined by a distance *r*), which provides a determined maneuver, decreases as time elapses, and an aircraft approaches its CPA.

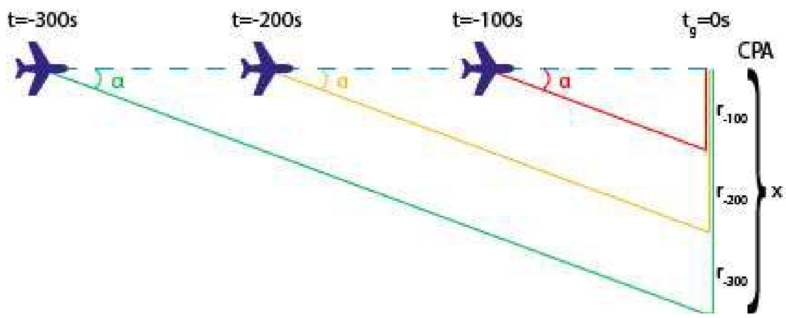

Figure 2-2: Time compression in generation of the number of resolution based on a certain maneuver type

Making basic trigonometric manipulations it is possible to determine an expression according to the distance *r* in function of the time:

$$\tan \alpha = r * dist_{current} \Rightarrow r(t) = \tan \alpha * dist_{current}$$

where the current distance, $dist_{current} = dist_{initial} - t * v$, and initial distance $dist_{initial} = (t_f - t_0) * v$. t_0 and t_f are starting and ending moments of the ecosystem time, and v is an aircraft speed. This approach has been used to quantify the weight that a determined maneuver provides as a function of time.

Both the maneuver of a conflict for a determined ecosystem and the weight this maneuver provides to the total number of solutions, need to be accurately differentiated. The solution to a conflict for a certain ecosystem is defined as one of the possible logical combinations of maneuvers the different aircraft can choose, to prevent a conflict from taking place.

2.3 Ecosystem modeling assumptions and criteria

The ecosystem framework relies on the following assumptions:

- Traffic scenario is described by 4-D trajectories (i.e. 4-D flight plans);
- The conflict time windows are computed within LAT, and present the subintervals in which potential induced conflicts could be generated, counted from the ecosystem identification moment until the CPA;
- Only pairwise conflicts are considered;
- Trajectories inside the cluster and ecosystem volumes are computed as linear segments. This assumption is adopted for a certain LAT value which, in general, is configurable.

In addition, the following criteria are used for the evaluation of the ecosystem interdependencies:

- A separation infringement occurs if horizontal distance between two aircraft is less than 5 NM and vertical distance less than 1000 ft;
- Scenarios are evaluated considering the maximum LAT of 300 seconds. However, the ecosystem framework can be tailored to different LAT values considering aircraft performances, ATC workload and performances and a certain level of the in-flight uncertainties[3].
- It is assumed a constant aircraft speed during the LAT inside the cluster volume (or, over ecosystem time).
- Safety buffers building the cluster volume are set to 15 NM laterally and 3000 ft vertically with respect to the CPA positions;
- An avoidance manoeuvrability in a 3-D space is defined by a set of assigned changes either in the aircraft heading or the vertical rate.

Uncertainties in the performance parameters, such as a time change in vectoring a particular avoidance maneuver, are not considered. The aircraft as a complex inertial system takes a certain amount of time in achieving the requested maneuver which arises the question about dynamicity of the ecosystem scenario and its membership configuration. However, for the sake of simplicity, the avoidance maneuvers in this thesis are assumed instantaneously effective. The objective is to identify the complexity levels of different ecosystems since the spatiotemporal interdependencies might differ between different sets of parametric values for the cluster creation and the ecosystem identification. Furthermore, potentially more demanding maneuvers due to higher parametric values could possibly generate more interdependencies and, consequently, provide less trajectory amendments as resolutions.

[3] No uncertainties have been considered as the ecosystem modeling framework presents an exploratory research concept that is deterministically formalized. However, the advanced stochastic models that include different uncertainty levels, such as weather model, navigation and positioning errors model, etc., will complement the concept of operations in the future.

3. Surrounding traffic complexity analysis for efficient and stable conflict resolution

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Surrounding traffic complexity analysis for efficient and stable conflict resolution

Marko Radanovic*, Miquel Angel Piera Eroles, Thimjo Koca, Juan Jose Ramos Gonzalez

Department of Telecommunications and Systems Engineering, Autonomous University of Barcelona, Sabadell (Barcelona), Spain

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Surrounding traffic

ABSTRACT

The constant increase in air traffic demand increases a probability of the separation minima infringements in certain areas as a consequence of increased traffic density. The Annual Safety Report 2016 reports that in recent years the number of infringements, measured per million flight hours, had been increased at a lower rate (Eurocontrol, 2018). However, this level of infringements still generates a continuous pressure on the air traffic control (ATC) system and seeks for more control resources ready to tactically solve potential conflicts, while increasing at the same time the operational costs. Considering present air traffic management (ATM) trade-off criteria: increased airspace capacity and traffic efficiency but reducing the cost while preserving safety, new services must be designed to distribute the separation management ATC task loads among other actors. Based on the Single European Sky Air Traffic Management Research and Next Generation Air Transportation System initiatives, this paper proposes an innovative separation management service to shift the completely centralized tactical ATC interventions to more efficient decentralized tactical operations relying on an advanced surrounding traffic analysis tool, to preserve the safety indicators while considering the operational efficiency. A developed methodology for the proposed service is an application-oriented, trying to respond to characteristics and requirements of the current operational environment. The paper further analysis the traffic complexity taking into consideration the so-called domino effect, i.e. a number of the surrounding aircraft causally involved in the separation management service by the means of identification of the spatiotemporal interdependencies between them and the conflicting aircraft. This complexity is driven by the interdependencies structure and expressed as a time-criticality in quantifying the total number of the system solutions, that varies over time as the aircraft are approaching to each other. The results from two randomly selected ecosystem scenarios, extracted from a simulated traffic, illustrate different avoidance capacities for a given look-ahead time and the system solutions counts, that in discrete moments reach zero value.

1. Introduction

The main air traffic management (ATM) mission is to provide a set of services to preserve the required separation between aircraft to meet safety target levels, while competitiveness of the air transport is maintained by means of an efficient system, environmentally

* Corresponding author.
E-mail addresses: marko.radanovic@uab.cat (M. Radanovic), miquelangel.piera@uab.cat (M.A. Piera Eroles), thimjo.koca@uab.cat (T. Koca), juanjose.ramos@uab.cat (J.J. Ramos Gonzalez).

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friendly and socially valuable (Di Gravio et al., 2015; Cook et al., 2017). Safety performance indicators are achieved through a set of mechanisms for the prevention of imminent hazardous situations that could evolve towards major incidents or even accidents (Gluchshenko & Foerster, 2013). These mechanisms are known as safety nets (Eurocontrol, 2013) and are structured in four main layers according to an operational time horizon:

- Strategic level: hours before flight departure, a ground regulation can be issued if a demand is greater than the available capacity and the system is in a maximum deployment state. By limiting the number of aircraft crossing an air traffic control (ATC) sector, the probability of a separation minima infringement can be reduced, but it cannot guarantee a conflict avoidance.
- Tactical level: medium term conflict detection (MTCD) function usually starts 20 to 15 min prior to a potential safety event occurrence, in which the air traffic controllers issue directives to one of the aircraft involved in a conflict to preserve safety distance.
- Pre-operational level: short term conflict alert (STCA) usually fires a warning to the ATC 120 to 90 s before a collision might occur.
- Operational level: Traffic alert and Collision Avoidance System (TCAS), is the last service to avoid a pairwise collision. The main difference with respect to previous safety net layers, is that TCAS is airborne system that functions independently of the ground-based safety nets, and provides collision avoidance protection for a broad spectrum of aircraft types.

Despite the excellent safety indicators achieved by the present safety net mechanisms, it is recognized that a lack of integration between the different safety layers introduces several penalties in key performance areas such as capacity (latent capacity) and operational efficiency (delays and maneuvers out of preferred trajectories). Furthermore, the pressure to accommodate more flights to satisfy the increment of air transport demand (Eurocontrol, 2018), will strain the loose ties between the safety nets with a negative impact on safety indicators. It is notable, for example, that present TCAS II v.7.1, has been designed for operations in the traffic densities of 0.3 aircraft per squared nautical mile [NM^2] (Tang et al., 2016). TCAS demonstrates excellent performances in cases of the pairwise encounters but, unfortunately, shows some operational drawbacks in its logic due to well reported induced collisions from specific surrounding traffic (ST) scenarios with higher density (Murugan, 2010). In (Jun et al., 2014), there are illustrated several ST scenarios in which TCAS resolution advisories (RAs) can induce a conflict.

To address these drawbacks in present and future air traffic, further research in the ATM sector is required towards development of a collaborative, proactive and decentralized separation management system considering a socio-technological approach in which both human behaviour and automation will play an important role (Prandini et al., 2011; Brázdilová et al., 2011). That envisages an operational seamless integration of the safety net mechanisms and procedures in such a way that any pair of aircraft involved in a conflict, together with the ST aircraft, behave as a stable and efficient conflict free air traffic system.

This article introduces an ATM framework relying on the concept of aerial ecosystems to transform opposite targets between a separation management function at the tactical level, and a collision avoidance function at the operational level, into a seamless cooperative efficient conflict-free framework. The framework is based on the so-called explicit coordination in conflict resolution. In many cases, the explicit coordination is an approach which is generally avoided for the main reason: the time it might take to solve a cluster of conflicts (Kuchar & Yang, 2000; Zeghal, 1998). Waiting for a new resolution means it could become more extreme than might have been necessary. Nevertheless, the available solutions space is being compressed in time.

A vector-based approach with an implicit coordination has also been shown to be able to solve the multi-aircraft conflicts in an effective and efficient way without the risks of deadlocks and waiting times. For instance, the modified voltage potential (MVP) is one of the approaches that was implemented for the conflict resolution in the multi-aircraft environment (Sunil et al., 2015). Within this approach, the conflict detection is performed by a state-based extrapolation of traffic positions, within a prescribed look-ahead time (LAT), using traffic transmitted state information (position, speed and heading). MVP is subsequently used to resolve conflicts in a pairwise manner. This method results in the implicit cooperative resolution strategies, where the distance between the conflicting aircraft at the CPA is increased to, at least, the minimum separation requirements. However, the concept extends the TCAS logic since LAT in this case is set to 60 s before the CPA, which practically means the method does not consider the SM-CA integration. Furthermore, less available space for the cooperative resolution exists, and consequently, the business preferences of the airspace users cannot be considered.

Another factor delimiting this approach in the effect of swarming (Maas et al., 2016). To cooperatively resolve the conflicts before collision avoidance, the aircraft are required to align their velocities and adjust their inter-distances for computation of the moment for triggering the cooperative resolutions. On the contrary, the ecosystem concept elaborated in this paper extends the time horizon providing more decision capacity at the SM level. The aircraft are aware of a potential deadlock moment while flying to the CPA, and given a possibility to interactively negotiate the solution, not requiring a priori any adjustment in velocity or heading and following the trajectories as approved. Moreover, identification of a higher number of the causally involved aircraft into enlarged ecosystem volume provides an opportunity for an efficient modeling of the optimal resolution trajectories, usually with the minimal deviations.

In recent years, more research efforts have been done in the field of the cooperative flights for unmanned aerial systems (UAS), focusing on development of the efficient trajectory planning and collision avoidance algorithms. Most of algorithms apply optimization techniques to generate the smother (or, less deviated) and safer trajectories. Sun et al. (2017) developed a collision avoidance algorithm for cooperative UASs based on an optimized artificial potential field (APF). The algorithm identifies both the static and dynamic (another UAS companions) obstacles from the single UAS perspective, as an ownship, and preservers from collisions. As such, it updates the trajectories in a planning phase by modifying the UAS state variables and smoothing the trajectory or mission profiles. However, the closure rates or relative speeds among UAS companions are not fully considered taking into consideration a speed change or acceleration of an UAS, after collision avoidance with a static obstacle. Moreover, the algorithm proposes a basic concept of APF to consider the movement of an UAS in the planning space as a type of force motion in the virtual force field. The UAS moves to the target point under the composition of the attractive and repulsive force, which is not applicable for the manned commercial aircraft due to a wide range of the inertial force values. Nevertheless, the algorithm is more applicable at the pre-tactical rather than tactical or operational level for a certain lookahead time. A combination of the static and dynamic obstacles avoidance in the urban environments does not impose a robust safety net at tactical level due to the frequent changes in the UAS state information and intent, which is characteristic for an unmodeled dynamics.

Tang (2017) summarizes different conflict detection and resolution methods with respect to the different safety nets, and then analyses the TCAS improvements in terms of the current operational performance achievement. Beside the vertical RAs, the improved TCAS performances consider the conventional horizontal RA expansion and other improved strategies in the multi-aircraft conflict environments, such as the combination of a radar with the Global Positioning System (GPS)-based TCAS functionality, or Automatic Dependent Surveillance – Broadcast (ADS-B) and TCAS coupling. Those strategies are analysed from a technological point of view, for executing the advanced RAs and eliminate a possibility for the induced collision as a domino effect. However, the time and space compression in approaching to TCAS operational domain still limit a capability for a comprehensive analysis of the larger-scale surrounding traffic characteristics, and development of robust mid-air collision-avoidance methods. An extension of time horizon is necessary for increased avoidance capacity. On contrary, the concept of the aerial ecosystem tries to integrate the existing TCAS performance with the SM function in a longer time horizon, trying to identify the extent to which collision avoidance function can be triggered. This extent is proportional to the loss of conflict resolution capacity. Therefore, it is necessary to fully consider at a microscopic level all trajectories in a nearby airspace whose can be causally involved in the conflict, that after some time interval might escalate into collision.

The aerial ecosystems can be understood as a paradigm of the complex adaptive systems, in which the clustered aircraft trajectories change and evolve over time because of the interactions between them and its ever-changing environment. An aerial ecosystem, as a tactical air traffic, multi-agent system (Pritchett & Feigh, 2014), presents a set of aircraft with the trajectory-amendment and decision-making capability, whose trajectories are identified inside a computed airspace volume, cluster, and causally involved in a safety event. The concept is built on a predicted conflict between two aircraft, whose trajectory segments are used for the detection of the surrounding aircraft through identification of the spatiotemporal interdependencies (STIs). The interdependencies are determined by the combinations of the potential avoidance maneuvers between the conflicting aircraft and duration of the conflict intervals. The determination process is subsequently further extended to each pair of aircraft involved in a detected conflict. Consequently, the ecosystem aircraft aim at formation of a cost-efficient separation management that allows cooperative actions in the generation of resolution trajectories. The principal objective is to enhance the aircraft decision-making capability to safely exploit the nearby airspace availability. The paper describes the aerial ecosystem identification process as a transitional procedure from the conflict detection, the surrounding traffic analysis, to the ecosystem memberships identification in a simulated trajectory-based operations (TBO) environment (Lyons, 2012; Ramasamy et al., 2014). First, a sampling procedure for the input 4-D trajectories is explained, followed by the state-based conflict detection algorithm, as well as detailed a stepwise identification of the interdependencies used to analyse the ecosystem complexity. The ecosystem transition presents a quantification of a number of the ecosystem aircraft from a number of cluster aircraft (i.e. the aircraft in conflict together with the surrounding aircraft). The complexity is considered as a time-criticality in quantifying a total number of the system solutions at discrete time instances, that varies over time as the aircraft are approaching to each other. The results from two randomly selected ecosystem scenarios extracted from a simulated traffic illustrate different avoidance capacities for a given LAT and the system solutions counts, that at certain moments reach zero value.

In addition to this introductory section the article comprises four other sections. Section 2 describes the operational emergent dynamics based on TCAS logic, affected by the surrounding traffic characteristics. Section 3 explains objectives, assumptions and metrics used for development of tactical conflict management, while Section 4 describes the ecosystem framework and its complexity evaluation. Section 5 discusses the simulation results, and concluding remarks and directions for the further research are given in Section 6.

2. Operational emergent dynamics induced by surrounding traffic unmodeled behaviour

TCAS was designed to work independently from the aircraft navigation equipment on-board as well as the ATC systems. It computes a time to a closest point of aprroach (CPA) with the traffic aircraft (*intruder*) as a ratio between the range and closure rate, or range rate (Kochenderfer et al., 2010; Kochenderfer & Chryssanthacopoulos, 2010). This time is denoted with *tau* and it is the main parameter for the TCAS alerts. CPA is an estimated point at which the distance between two aircraft in conflict will reach its minimum value. Both range and range rate in horizontal plane are obtained from TCAS interrogations, usually with one-second update, and they apply to aircraft in crusing configuration. In vertical plane, the time to co-altitude (vertical tau) is computed as a vertical separation divided by a vertical closure rate (Munoz et al., 2013). TCAS issues two types of alerts:

- traffic advisories (TAs) helping pilots in a visual search for the intruder and to prepare them for potential RAs;
- RAs that recommend manoeuvres leading to either increase or maintenance of the existing vertical separation from an intruder aircraft.

TAs or RAs are displayed only when both range tau and vertical tau are below certain threshold values that depend on the sensitivity level (SL). This one-digit number features a strength sense of a TCAS command (Geser et al., 2006). Table 1 provides the

Table 1
TCAS advisories.

Altitude [ft]	SL	TAU [sec]		DMOD [nmi]		ZTHR [ft]		ALIM [ft]
		TA	RA	TA	RA	TA	RA	RA
1000–2350	3	25	15	0.33	0.20	850	600	300
2350–5000	4	30	20	0.48	0.35	850	600	300
5000–10,000	5	40	25	0.75	0.55	850	600	350
10,000–20,000	6	45	30	1.00	0.80	850	600	400
20,000–42,000	7	48	35	1.30	1.10	850	700	600
> 42,000	7	48	35	1.30	1.10	1200	800	700

TA and RA tau thresholds for each sensitivity level.

However, when the closure rate is very low, the intruder aircraft can approach very close in range to the *ownship* aircraft without crossing the tau boundaries and, consequently, without triggering the TA and RA alerts. To provide protection in such encounters, a modification in both range and vertical separation was introduced in TCAS II. In first case, a distance modification (DMOD) allows TCAS to issues TAs and RAs at, or before, the fixed range threshold in the slow rate encounters, while in second case, for slower vertical tau, a fixed altitude threshold – ZTHR - gives a possibility for triggering TA and RA (Espindle et al., 2009). Like *tau*, both DMOD and ZTHR vary for different SLs (Table 1). In preventing near mid-air collisions, the logic of TCAS relies on three common rules for pairwise encounters (Tang et al., 2015), as illustrated in Fig. 1:

(1) Two RAs are opposite to each other; they advise an opposite sense for maneuvers to the crew, i.e. climb-descend or descend-climb.
(2) When RAs are issued, the aircraft at a lower altitude performs descent and the one at higher altitude climb, without considering the current flight configuration: cruise, climb or descent.
(3) Two aircraft after the RA activation must achieve a minimum vertical separation at CPA (Table 1) called altitude limitation (ALIM), measured in feet (ft).

As it can be observed in the TCAS operational logic, it is not considered the ST dynamics at all, because of an assumption that the strategic safety net limits the amount of aircraft in a certain sector according to the declared capacity. Nevertheless, the strategic limit in the sector does not prevent at the operational level the ST impact on the TCAS performance logic.

To illustrate the concept of operational emergent dynamics leading to an induced collision it is considered a theoretical example. The example is extracted as an initial state of a non-vectored traffic scenario. The scenario can be operationally assumed as a transition from TMA to the en-route airspace, with a high conflict probability due to higher traffic densities and evolving aircraft configuration (climbing and descending flight mode). Fig. 2 illustrates a scenario with four aircraft, A/C01, A/C02, A/C03 and A/C04, flying over trajectories that form two predicted encounters A/C01-A/C02 and A/C03-A/C04. A/C01 is cruising on FL160 while A/C02 starts descending at FL180 in the opposite direction from A/C01, which assumes a direct approch to A/C01 with a loss of height. On the other side, A/C03 starts climbing at FL130, and, with its increase in height, approaching to A/C04, which is crusing at FL153 in opposite direction from A/C01.

As it can be seen, both conflicts are successfully resolved after activation of TAs, at the time stamps of four aircraft t_{TA}^{01}, t_{TA}^{02}, t_{TA}^{03} and t_{TA}^{04}, respectively, and then followed by the corresponding RAs, at the time stamps t_{RA1}^{01}, t_{RA}^{02}, t_{RA}^{03} and t_{RA1}^{04}. The required minimal vertical distance, ALIM, has been successfully achieved at both CPAs.

As a CA layer activates in less than 60 s and RAs are issued in less than 35 s before CPA (Table 1), once resolved conflicts produce very high uncertainty in guidance over amended Reference Business Trajectories (RBTs). After their amendments, A/C01 and A/C04 generated a new conflict, denoted as an induced conflict. It presents a product of downstream flow effect and is characterized by the instantaneous TA or RA alert, while the aircraft is still performing requested resolution manoeuvre, and not resumed to its RBT (Peng & Lin, 2010). In this case, both aircraft are automatically alerted by the succeeding RAs, at time stamps t_{RA2}^{01} and t_{RA2}^{04}, respectively. Unfortunately, due to insufficient time for the appropriate succeeding manoeuvres a collision between two aircraft could arise.

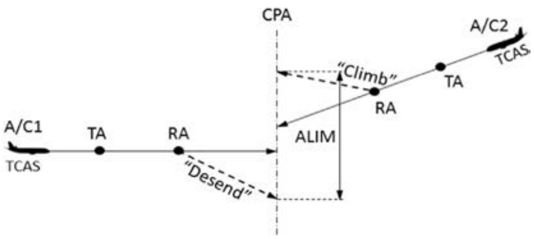

Fig. 1. TCAS RA sense selection.

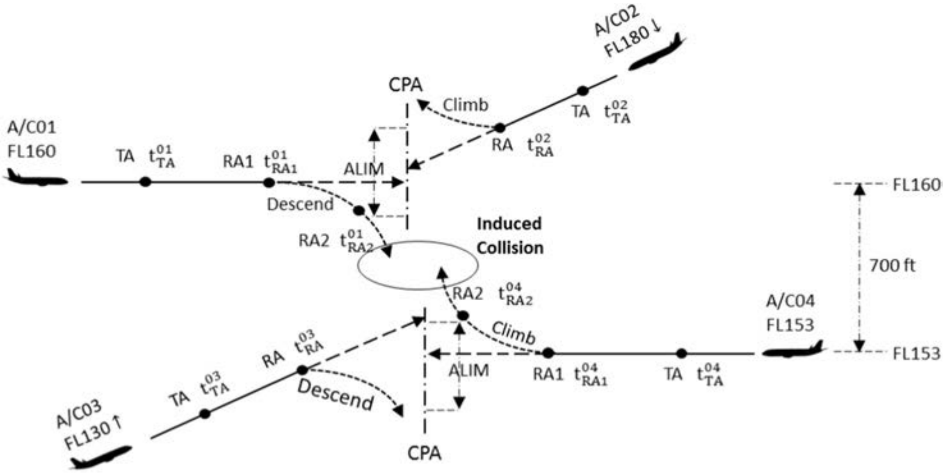

Fig. 2. Two pairwise encounters forming induced collision scenario (Tang et al., 2014).

As previosly stated, the scenario is the theoretical example and serves for the purpose of TCAS logic analysis only, and justify that better separation management mechanisms should be designed to avoid firing TCAS in these operating conditions. It does not reflect the real-world case, since such scenarios are notably rare in practice (Tang et al., 2014). For instance, A/C04 was intially cruising at FL153 which is not standard, either cleared or request flight level (CFL vs. RFL), and, in practice, this can occur in case A/C04 had resolved a previous conflict (before having the conflict with A/C03) that resulted in *Level-off* RA. Here, FL153 is issued to denote a corresponding SL with respect to A/C01 and the altitudes range in which the scenario took place.

Introducing more conservative limits about the amount of aircraft coexisting in a volume airspace would be a natural mechanism to mitigate emergent dynamics caused by the ST effects. However, the latent capacity and low efficiency indicators discourage this approach. Instead, a deep understanding of the ST behaviour paves the way for an efficient ATM automation system. Furthermore, the deadlock scenarios in which the coexistence of actions can drive the system state to a blockage is not a particular problem of ATM, It has been rather studied by the means of the state space analysis tools in different applied fields (Narciso et al., 2012). The use of formal methods in the analysis of surrounding traffic enhances the implementation of conflict resolution tools that could guarantee deadlock-out scenarios. Considering again the example illustrated in Fig. 2, it is highlighted the importance to identify for each encounter geometry the time limit at which the RA should be fired, to avoid an induced collision or unacceptable safety levels.

On the other side, the current safety management systems do not have the functionalities neither the capabilities to comprehensively analyse surrounding traffic across the full airspace, to identify potential induced collisions as effect of pairwise conflict management. The common practice implemented by the air traffic controllers is identification of the safety event using the time thresholds (i.e. MTCD and STCA), and provision of separation by assigning the standard, but instantaneous, horizontal and vertical manoeuvres. For instance, the state-based properties in conflict resolution, such as heading and speed, are provided instantaneously, in a procedural way, but without any supporting tool to analyse the ST dynamics with the trajectory geometries (Erzberger et al., 2012).

3. Aerial ecosystem concept

3.1. Tactical conflict management framework

The aerial ecosystem framework relies on the analysis of interdependencies between aircraft positioned in the airspace volume, proximate to a detected pairwise conflict that will fairly 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 operationally predict an ST emergent behaviour and identify a subset of trajectory amendments that will not cause a negative domino effect with the neighbouring aircraft (Ruiz et al., 2013). In (Ghosh & Tomlin, 2000), it is shown that the earlier in advance of a predicted conflict the resolution manoeuvres are considered, the smaller will be the probability in violating the standard separation minima (SSM) with the ST aircraft. From this fact, an objective of a tactical conflict management framework emanates: to build the spatiotemporal causal model that comprises all aircraft whose trajectory amendments could converge to loss of separation.

The transitional procedure implemented towards a tactical conflict management layer, in which aerial ecosystem members will be enhanced to coordinate efficient resolutions is summarized in three stages:

- *State-based conflict detection*: detection function that searches for a loss of separation among the pairs of sampled trajectories. The algorithm takes as parameters the current position of two aircraft, and returns a value indicating loss of separation between them. The trajectories are interpolated each second. Prediction is also characterized by the constant advanced time interval, LAT, continuously projected over trajectories.

- *Cluster creation*: a set of extracted trajectories filtered both in time and space around detected pairwise conflict. The cluster volume is defined by the extrapolated points along trajectories, shifted timely back for a LAT interval, and computed safety buffers, added to these points.
- *Aerial ecosystem identification*: cluster trajectories with potential interdependencies in which any of two conflicting aircraft making a potential trajectory amendment could force the direct or indirect trajectory amendment of another cluster member. As a result, a subset of cluster members will be identified as ecosystem members through generation of the interdependencies structure.

3.2. Aerial ecosystem modeling assumptions and criteria

The tactical conflict management framework relies on the following assumptions:

- Traffic is described by 4D trajectories (i.e. 4-D flight plans);
- The conflict time windows are computed within the ecosystem time, and present the subintervals in which potential induced conflicts could be generated, counted from the ecosystem identification moment, t_{EIP}, until the closest point of approach timestamp, t_{CPA};
- Only pairwise conflicts are considered;
- For the conflicts prediction, both the aircraft encounters and over-takings are analysed;
- Trajectories inside the cluster and ecosystem volumes are computed as the linear segments.

In addition, the following criteria are used for the evaluation of the ecosystem interdependencies:

- Loss of separation occurs if horizontal distance between two aircraft is less than 5 NM and vertical distance less than 1000 ft;
- Scenarios are evaluated considering the maximum LAT of 300 s. In general, the ecosystem process can be tailored to different LAT ranges considering aircraft performances.
- It is assumed constant speed of all aircraft identified inside the cluster volume.
- Safety buffers building the cluster are set to 15 NM laterally and 3000 ft vertically with reference to the CPA positions;
- For simulation purpose, the interdependencies are not analysed in less than 60 s before two aircraft in conflict reach their CPAs; therefore, if not earlier, the number of system solutions reaches zero value latest 240 s after the ecosystem identification.
- An avoidance manoeuvrability in a 3D space is defined by a set of assigned changes either in the aircraft heading or the vertical rate.

4. Ecosystem framework and complexity evaluation

4.1. Pairwise conflict detection algorithm

The first step for the ecosystem identification is a conflict detection among a pair of aircraft. As already explained, the concept is based on the TBO environment relying on the 4D trajectory management (Ramasamy et al., 2013), in which each point along trajectory is defined by a 3D position (i.e. by the latitude, longitude and altitude coordinates), and a required timestamp for overfly. A predictability to reach each point at required time of arrival is fully assumed without any uncertainties or deviations. That means that a linearity in the horizontal and vertical trajectory profile is fully assumed, that presents the shortest segment length between two waypoints (WP). Considering the aircraft state position and velocity information, embedded into the 4D flight plans, and the closure rates between two aircraft the algorithm is based on the Euclidean state-based conflict detection applied to each pair of trajectories (Kuchar & Yang, 2000; Narkawicz et al., 2013). Since the input data from the flight plans are provided as the geographic coordinates, i.e. latitude (φ), longitude (λ) and altitude (h), it is necessary to transform those coordinates into the Euclidean 3D space (x, y, z). The most common and widely applied approach is the stereographic projection, which is a particular mapping or function that projects a sphere onto a plane (Kosel, 1984). The transformation equations for a sphere of the radius R are given by:

$$\begin{aligned} x &= k\cos\varphi\sin(\lambda-\lambda_0) \\ y &= k\left[\cos\varphi_0\sin\varphi-\sin\varphi_0\cos(\lambda-\lambda_0)\right] \\ z &= h*100 \end{aligned} \tag{1}$$

where λ_0 is the central longitude, φ_0 is the central latitude, and the coefficient k can be expressed in the following form:

$$k = \frac{2R}{1 + \sin\varphi_0\sin\varphi + \cos\varphi_0\cos\varphi\cos(\lambda-\lambda_0)} \tag{2}$$

Therefore, after the transformation $\lambda \rightarrow x$, $\varphi \rightarrow y$, $h \rightarrow z$ and the corresponding conversion into the required units, i.e. x and y to [NM] and z to [ft], it is possible to implement the conflict detection algorithm for the analysed traffic scenario. Once transformed, the input 4-D points belonging to each trajectory have a form: WP [x, y, z, t]. The conflict detection algorithm is based on the trajectory sampling and computation of the loss of separation at the current aircraft position. Separation minima are adopted by convention in the en-route airspace: 5 NM horizontally, and 1000 ft vertically. In other words, if and only if both the horizontal and vertical inter-distances between two aircraft positions are below the given thresholds at a certain time instant, the aircraft are treated as conflicting.

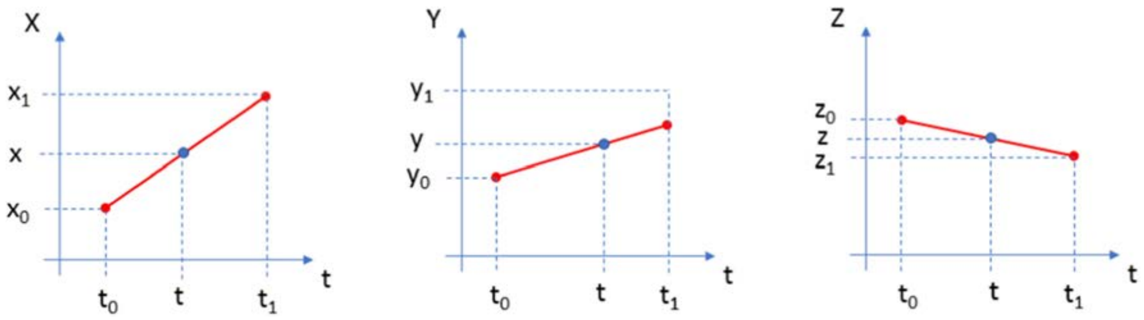

Fig. 3. Linear interpolation in 3D Euclidean space.

The algorithm implements the linear interpolation by one-second rate between each two consecutive waypoints. That means a new set of the 3D intermediate points is generated each second. The interpolation is applied along each axis. Using the interpolation for each consecutive point in the trajectory sampling, the following system of equations describes the method:

$$\begin{aligned} x &= x_0 + \frac{x_1 - x_0}{t_1 - t_0} \\ y &= y_0 + \frac{y_1 - y_0}{t_1 - t_0} \\ z &= z_0 + \frac{z_1 - z_0}{t_1 - t_0} \end{aligned} \tag{3}$$

where x_0, y_0, z_0 present the coordinates of the first WP, and x_1, y_1, z_1 the coordinates of the second WP. x, y, z denotes a 3-D position of an interpolated point. The computation can be graphically illustrated in Fig. 3.

Once sampled, each pair of trajectories is analysed for a loss of separation between the current positions of two aircraft. Suppose that two sampled trajectories can be expressed as an array of 4D points:

$$\begin{aligned} T_1 &= [(x_{10}, y_{10}, z_{10}, t_{10}), \cdots, (x_{1i}, y_{1i}, z_{1i}, t_{1i}), (x_{1,i+1}, y_{1,i+1}, z_{1,i+1}, t_{1,i+1}), \cdots, (x_{1k}, y_{1k}, z_{1k}, t_{1k}), \cdots, (x_{1n}, y_{1n}, z_{1n}, t_{1n}), i \in [0, n] \\ T_2 &= [(x_{20}, y_{20}, z_{20}, t_{20}), \cdots, (x_{2j}, y_{2j}, z_{2j}, t_{2j}), (x_{2,j+1}, y_{2,i+1}, z_{2,j+1}, t_{2,j+1}), \cdots, (x_{2l}, y_{2l}, z_{2l}, t_{2l}), \cdots, (x_{2m}, y_{2m}, z_{2m}, t_{2m}), j \in [0, m] \end{aligned} \tag{4}$$

The aircraft A/C_1 and A/C_2 flying over T_1 and T_2, respectively, will face a loss of separation for $\forall\ t_{1i} = t_{2j}$ if:

$$\begin{aligned} &\sqrt{(x_{1i} - x_{2j})^2 + (y_{1i} - y_{2j})^2} < D \\ &|z_{1i} - z_{2j}| < H \end{aligned} \tag{5}$$

where $D = 5$ NM and $H = 1000$ ft present the horizontal and vertical separation minimum, respectively. Expressions (5) set the criteria in which the points P_{1i} $[x_{1i}\, y_{1i}\, z_{1i}\, t_{1i}]$ and P_{2j} $[x_{2j}\, y_{2j}\, z_{2j}\, t_{2j}]$ present the starting conflict points of A/C_1 and A/C_2, respectively, and $t_{1i} = t_{2j} = t_{in}$ the starting moment of the conflict. From this moment, the conflict interval is measured until the instant $t_{1k} = t_{2l} = t_{out}$. At that moment the following conditions must be met:

$$\begin{aligned} &\sqrt{(x_{1k} - x_{2l})^2 + (y_{1k} - y_{2l})^2} \geq D \\ &|z_{1k} - z_{2l}| \geq H \end{aligned} \tag{6}$$

Therefore, the points where the conflict interval terminates are P_{1k} $[x_{1k}\, y_{1k}\, z_{1k}\, t_{1k}]$ and P_{2l} $[x_{2l}\, y_{2l}\, z_{2l}\, t_{2l}]$. Within this interval the algorithm searches for the shortest 3-D distance, i.e. the distance between CPAs of two aircraft in conflict. Fig. 4 illustrates the horizontal and vertical profiles for a pair of trajectories evolved in time.

Once computed the starting and ending 4-D points of the conflict interval as well as their closest points of approach, the coordinates are transformed back to the geographic ones (except the z coordinate, that remains in [ft]) by the following set of equations:

$$\begin{aligned} \varphi &= sin^{-1}\left(cosC sin\varphi_0 + \frac{ysinC cos\varphi_0}{\rho}\right) \\ \lambda &= \lambda_0 + tan^{-1}\left(\frac{xsinC}{\rho cos\varphi_0 cosC - ysin\varphi_0 sinC}\right) \end{aligned} \tag{7}$$

where

$$\begin{aligned} \rho &= \sqrt{x^2 + y^2} \\ C &= 2tan^{-1}\left(\frac{\sqrt{x^2 + y^2}}{2R}\right) \end{aligned} \tag{8}$$

The transformation equations are recalled at the end of each step in the algorithm.

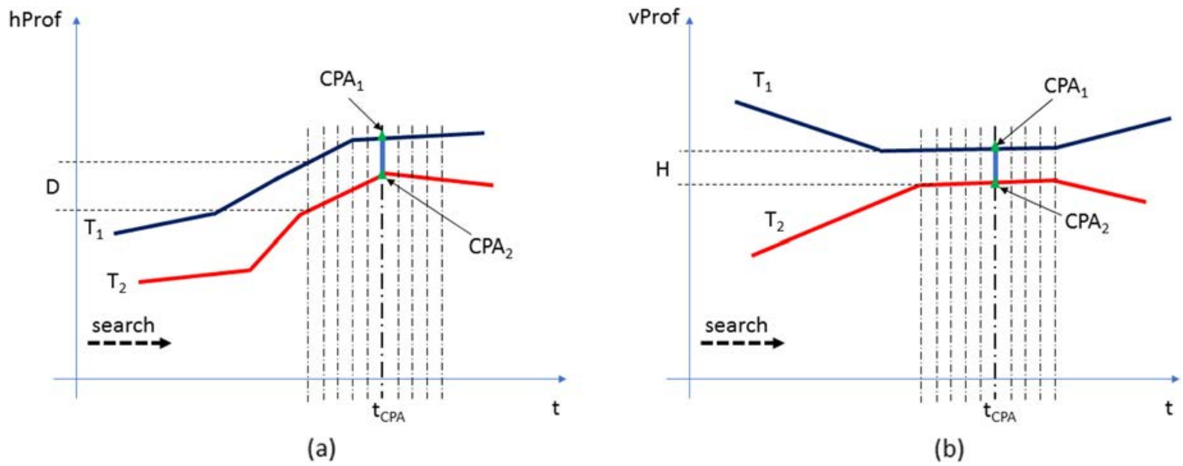

Fig. 4. Search for the conflict interval and CPAs among a pair of trajectories in (a) horizontal plane, (b) vertical plane.

4.2. Cluster creation function

The cluster creation function, as a spatiotemporal category, is to quantify the number of surrounding trajectories around a detected conflict (Gariel et al., 2011; Wei et al., 2014). The method used for creation of the airspace volume is rather conservative, as the idea behind is to causally analyse all surrounding trajectories with distinctive geometries and aircraft closure rates relative to the conflicting pair. The customization of the cluster space is done in line with the aircraft performances based on BADA (Base of Aircraft Data) values. A cluster is created considering a sequence of filters. For a given conflict, a 4D CPA for each aircraft (i.e. CPA_1 and CPA_2) is taken as an input. Given that, from t_{CPA1} and t_{CPA2} the new positions of both aircraft are predicted using the constant interval of 300 s as LAT. In other words, LAT is propagated from the CPA back for a definition of an ecosystem identification timestamp, t_{EIP}. The 3D positions at the ecosystem identification points (EIPs) are then identified for both aircraft in conflict, and the cluster volume is built by adding/subtracting the safety buffers to/from the maximal/minimal values of the EIP coordinates. φ_{min} is the minimal latitude identified in the interval $[t_{EIP}, t_{CPA}]$, λ_{min} is the minimal longitude, and h_{min} is the minimal altitude. Maximum values, namely φ_{max}, λ_{max} and h_{max}, are defined analogously. The ST members are analysed in the ecosystem framework as aircraft whose RBTs during the interval $[t_{EIP}, t_{CPA}]$ are identified through the 4D points, such that their latitudes, longitudes and altitudes are inside the cluster volume. The cluster creation is therefore performed through seven steps:

(1) Feeding the cluster creation function with the output data from the conflict detection procedure, namely $CPA_1[\varphi_{CPA1}, \lambda_{CPA1}, h_{CPA1}, t_{CPA1}]$ and $CPA_2[\varphi_{CPA2}, \lambda_{CPA2}, h_{CPA2}, t_{CPA2}]$;
(2) Time-based projection of LAT in a reverse way, i.e. $t_{EIP} = t_{CPA} - LAT$.
(3) Matching the corresponding coordinates at the ecosystem prediction instant for both trajectories, φ_{EIP1}, λ_{EIP1}, h_{EIP1}, φ_{EIP2}, λ_{EIP2}, h_{EIP2};
(4) Finding the minimal and maximal values of the spatial coordinates from Steps 1 and 3:

$$\begin{aligned} ||\varphi_{min}|| &= \min(\varphi_{CPA1}, \varphi_{CPA2}, \varphi_{EIP1}, \varphi_{EIP2}) \\ ||\varphi_{max}|| &= \max(\varphi_{CPA1}, \varphi_{CPA2}, \varphi_{EIP1}, \varphi_{EIP2}) \\ ||\lambda_{min}|| &= \min(\lambda_{CPA1}, \lambda_{CPA2}, \lambda_{EIP1}, \lambda_{EIP2}) \\ ||\lambda_{max}|| &= \max(\lambda_{CPA1}, \lambda_{CPA2}, \lambda_{EIP1}, \lambda_{EIP2}) \\ ||h_{min}|| &= \min(h_{CPA1}, h_{CPA2}, h_{EIP1}, h_{EIP2}) \\ ||h_{max}|| &= \max(h_{CPA1}, h_{CPA2}, h_{EIP1}, h_{EIP2}) \end{aligned} \quad (9)$$

(5) Addition/subtraction of safety buffers to/from the values in Step 4 to obtain the new vertices of a box-shaped cluster (index L denotes the lower level and U the upper one for each of the coordinates):

$$\begin{aligned} ||\varphi_L|| &= \varphi_{min} - 15[NM] \\ ||\varphi_U|| &= \varphi_{max} + 15[NM] \\ ||\lambda_L|| &= \lambda_{min} - 15[NM] \\ ||\lambda_U|| &= \lambda_{max} + 15[NM] \\ ||h_L|| &= h_{min} - 3000[ft] \\ ||h_U|| &= \varphi_{max} + 3000[ft] \end{aligned} \quad (10)$$

(6) Filtering of the extracted traffic sample between the following ranges:

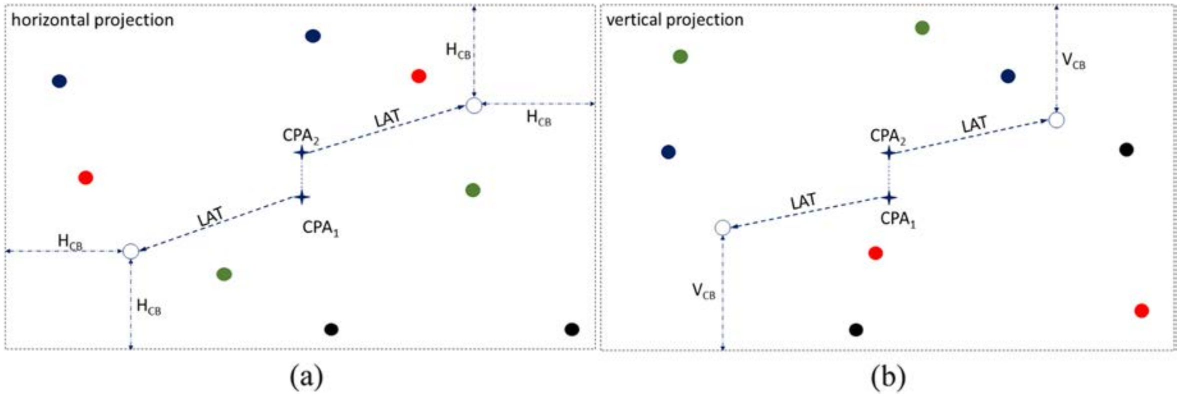

Fig. 5. Cluster creation procedure applied in (a) horizontal plane, (b) vertical plane.

- $\varphi_L - \varphi_U$ (*latitude* column);
- $\lambda_L - \lambda_U$ (*longitude* column);
- $h_L - h_U$ (*altitude* column);

(7) Identification of all 4D points inside the cluster volume and matching them with the corresponding flight identifiers to report the cluster members.

Computed safety buffers provide a full identification of all cluster members through dynamic analysis of the closure rates between the conflict and surrounding aircraft (Lizarraga & Elkaim, 2008; Gardi et al., 2014). Fig. 5 describes the cluster creation procedure in both the horizontal and the vertical plane. The shortest distance is detected between the points CPA_1 and CPA_2. The points around conflict aircraft match the surrounding trajectories.

Fig. 6 illustrates two cluster types in the horizontal plane with a similar spatial configuration, but with a different timestamp distribution that changes the membership structure. In the first scenario represented in Fig. 6a, there are two surrounding aircraft (ST_1 and ST_2) forming the cluster together with two aircraft in conflict. Additional ST_3 and ST_4 aircraft are out of consideration to become cluster members, as they are timely positioned far enough from the spatial cluster bounds. On the contrary, the second scenario represented in Fig. 6b, describes the cluster including ST_3 and ST_4 aircraft from the overtaking scenario since they timely reach the clustering area.

An important fact for the cluster creation procedure is an identification of the cluster aircraft belonging to two neighbouring clusters. As seen, a less rigorous approach in creation gives a possibility for such an occurrence, and an additional filter for this purpose has been introduced. The filter automatically assigns that aircraft to the cluster that is formed first (i.e. as per time occurrence). Another complex situation would be detection of two pairwise conflicts nearby to each other. In this case, two conflicts are modelled in a way that they form one large cluster, a supercluster, in which all identified trajectory and causally analysed.

4.3. Aerial ecosystem identification function

The ecosystem identification function determines all cluster members for which the loss of separation with any of two conflict aircraft would occur if that aircraft performs a feasible, conflict manoeuvre during within look-ahead time. The ecosystem membership is a spatiotemporal category as an applied manoeuvre generates conflict interval with a neighbouring aircraft.

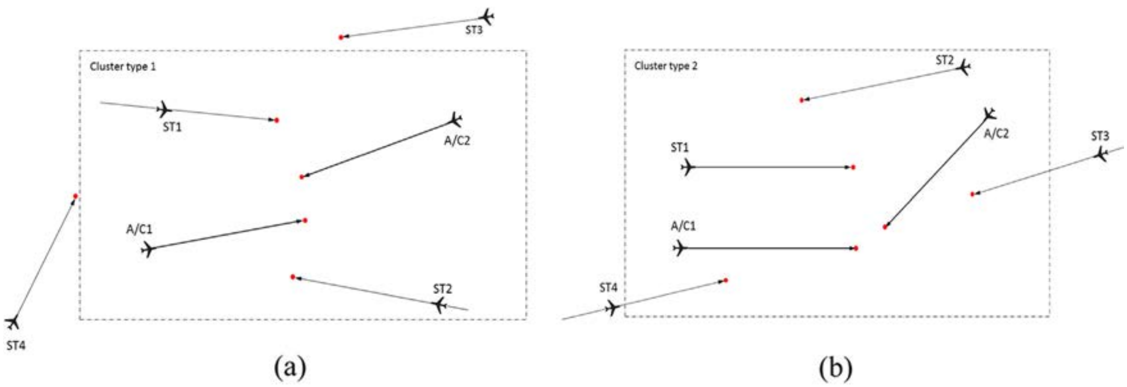

Fig. 6. Cluster (a) type 1, (b) type 2.

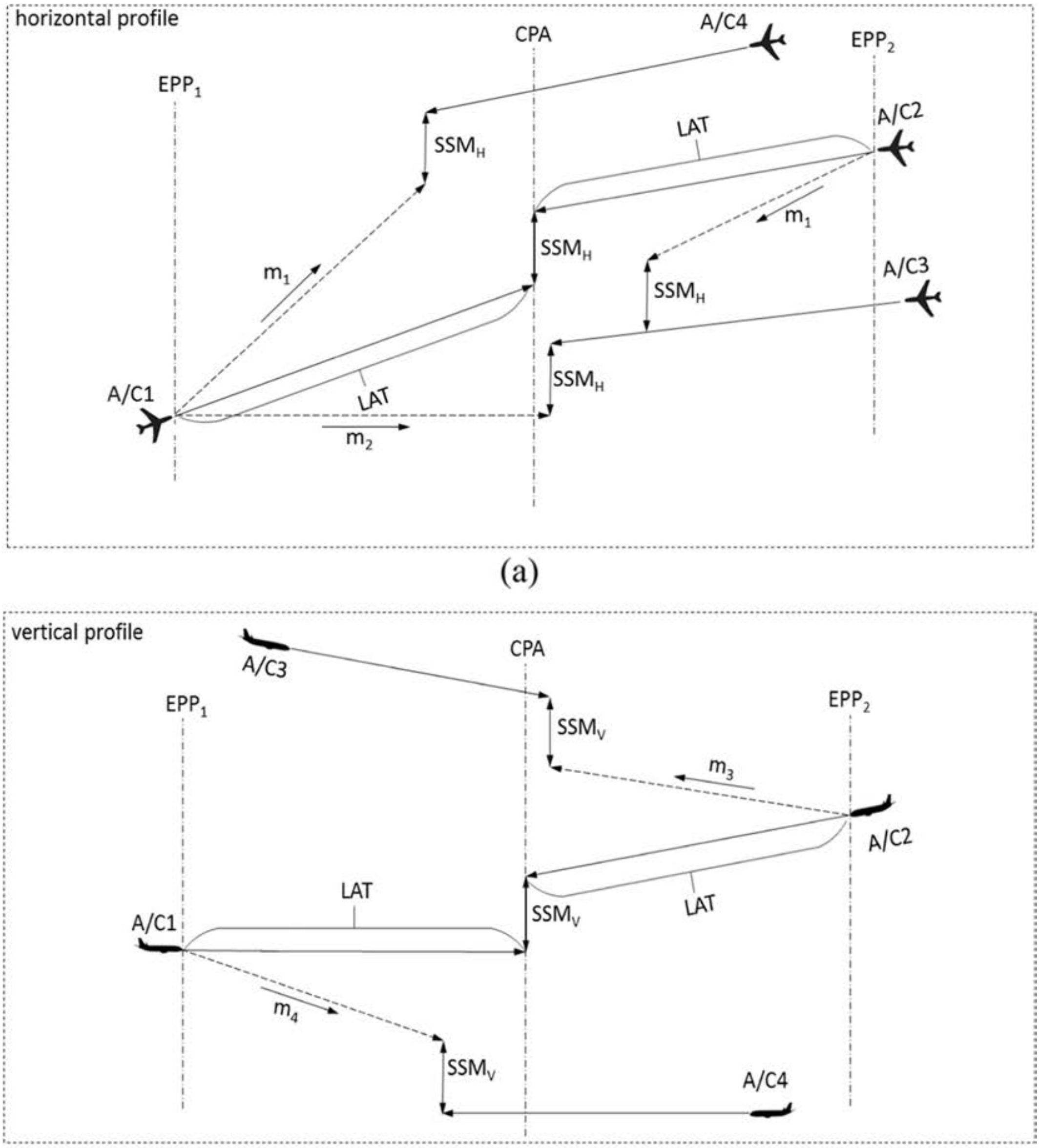

Fig. 7. Ecosystem identification procedure applied in (a) horizontal plane, (b) vertical plane.

Manoeuvrability in Fig. 7 is defined in both the horizontal and the vertical plane (Saarlas, 2007; Douglas et al., 1994), and used metrics are defined from the standard ATC separation procedures.

For the ecosystem identification, five avoidance manoeuvres are considered:

- $\mathbf{m_0}$: an RBT follow-up, meaning that aircraft continues flying over its RBT;
- $\mathbf{m_1}$: a counter-clockwise heading change with a deflection angle of $+30^{\circ}$;
- $\mathbf{m_2}$: a clockwise heading change with a deflection angle of -30°;
- $\mathbf{m_3}$: a climb at a vertical rate of $+1000$ ft/min, and a flight path angle of $+2^{\circ}$;
- $\mathbf{m_4}$: a descent at a vertical rate of -1000 ft/min, and a flight path angle of -2°.

Based on the metrics defined above, the cluster-ecosystem transition can be described as spatiotemporal process in which a surrounding aircraft identified as a cluster member becomes an ecosystem member, since its original trajectory is affected by an avoidance manoeuvre potentially performed by one of the aircraft in conflict. Therefore, the identification algorithm searches for those transitions and quantitatively outputs the number of ecosystems, levelled as per number of members, from the number of

Table 2
Example of STI structure.

STI_ID	Interdependent aircraft IDs	Maneuvering combination	Conflict interval [sec]
STI_1	A/C1–A/C2	$m_0 - m_0$	$t_{S1} - t_{E1}$
STI_2	A/C1–A/C3	$m_2 - m_2$	$t_{S2} - t_{E2}$
	A/C1–A/C3	$m_4 - m_4$	$t_{S3} - t_{E3}$
STI_3	A/C2–A/C3	$m_1 - m_2$	$t_{S4} - t_{E4}$

clusters within a given traffic scenario. As the number of ecosystem aircraft always evolves from a cluster size, the ecosystem set can only be less or equal to the cluster set, i.e. there could be mathematically formulated that ecosystem set *E* is a subset of cluster set *C*:

$$\forall\ ACi\{ACi \in E \rightarrow ACi \in C\} \Rightarrow E \subseteq C,\ \forall\ i \in [1, Nc] \tag{11}$$

where *N*c denotes the number of detected cluster aircraft. In general, $Nc = Nst + 2$, where *Nst* presents number of the surrounding traffic aircraft within a cluster. It is noteworthy to say, the values for the avoidance manoeuvres are configurable, meaning that the model can be simulated with different parametric values, and consequently analysed different outputs in the cluster-ecosystem size. In case that none ST aircraft is detected within a cluster volume (Nst = 0), both the cluster and ecosystem are composed of two aircraft in conflict only, $Nc = Ne = 2$. Ne denotes the number of ecosystem aircraft (Ne ≤ Nc). In case $Ne < Nc$ (there exists at least one cluster aircraft which is not an ecosystem aircraft), *E* is a proper (or strict) subset of C, i.e. E C. In case $Ne = Nc$, *E* is not proper subset of *C*.

The second part of the procedure refers to computation of time windows for each pair of members having interdependencies within $[t_{EIP}, t_{CPA}]$. Interdependencies are generated by comparison of a relative geometry between a pair of trajectory segments located inside the cluster, the type of a manoeuvre that each of monitored aircraft could perform to induce a separation infringement, and the time window during which the manoeuvre would generate a conflict. Table 2 describes the STI structure, where the first column presents an STI identifier, the second one a combination of the interdependent aircraft identifiers, the third one a manoeuvring combination of an aircraft pair inducing the conflict, and the last one the starting and ending moments of a conflict subinterval in which that manoeuvring combination is applicable.

As seen, one STI might have two or more conflict intervals as a product of different manoeuvring combinations. Fig. 8 shows two examples for computation of the conflict subinterval.

First example refers to the counter-clockwise heading change of A/C1 that would produce the loss of separation with A/C3 (provided that the vertical separation is already violated, i.e. below 1000 ft). Second example is the case of climb amendment of A/C1 and detected induced conflict with A/C4, assuming the horizontal separation is already affected, i.e. less than 5 NM.

4.4. Time-based ecosystem complexity and solutions

The ecosystem complexity can be analysed in scope of the time criticality. This characteristic is driven by an ecosystem size (a number of aircraft members), a geometry of the trajectories relative to each other, and the aircraft state information such as position, velocity and flight mode. As the ecosystem time is elapsing, the aircraft are approaching to the safety event and a collaborative decision-making for the satisfactory system solution at an early stage is usually desirable from both the qualitative and quantitative point of view. From qualitative perspective, the system solution is coherent for the aircraft performing trajectory amendments since the manoeuvres are less disruptive and more optimal with respect to RBTs. From quantitative point of view, a higher number of the acceptable solutions relying on the airspace users' preferences is selective. The decision must be acceptable for each member and reached before the aircraft come to the state in which one (or more) member is not able to remove the conflict situation by any feasible manoeuvre. This state is commonly denoted as an ecosystem deadlock event – EDE (Radanovic et al., 2018). It occurs either before or after the conflict aircraft enter the collision avoidance zone.

The analysis of the ecosystem evolution can be performed in a discrete space, i.e. tracking of the successive aircraft positions over one-second-trajectory samples. Furthermore, it is imposed a certain limitation. For a given set of avoidance manoeuvres only, the complexity must consider all potential combinations of those manoeuvres among the members that can induce the separation infringement (Gianazza, 2007). If the manoeuvrability checks are performed with the constant time rate of one second at each aircraft state, potential STIs can be analysed through combinations of five avoidance manoeuvres introduced in the previous subsection.

In theory, the maximum number of the ecosystem solutions that could be counted during LAT is reached at the ecosystem identification moment, since a longer time horizon (i.e. 300 s) towards CPA is available. Then, this quantity frequently decays over time, but at a random rate. This trend depends on the aircraft positions and velocities, flight configuration (climb, descent or cruise), as well as the relative geometries of the ecosystem trajectories. An ecosystem evolution toward computed EDE can be better illustrated on Fig. 9. The figure in vertical projection describes the evolution over three time-windows, TW1, TW2 and TW3, in which each subsequent window is a sub-window of the previous one. TW3 denotes a collision avoidance window whose edges present the EDE moment. Aircraft reaching this window on their RBTs are no more the subject to the ATC separation provision, but the TCAS activation. Therefore, any agreed (cooperative) maneuvers within TW3 will not provide the conflict-free amendments with respect to separation minima.

Corresponding to Fig. 9, Fig. 10 shows a theoretical decreasing rate of the conflict-free solutions over the ecosystem time. It can be noted a higher drop in the number of solutions that occur until the TW1, and then follow-up with a lower decreasing rate until the

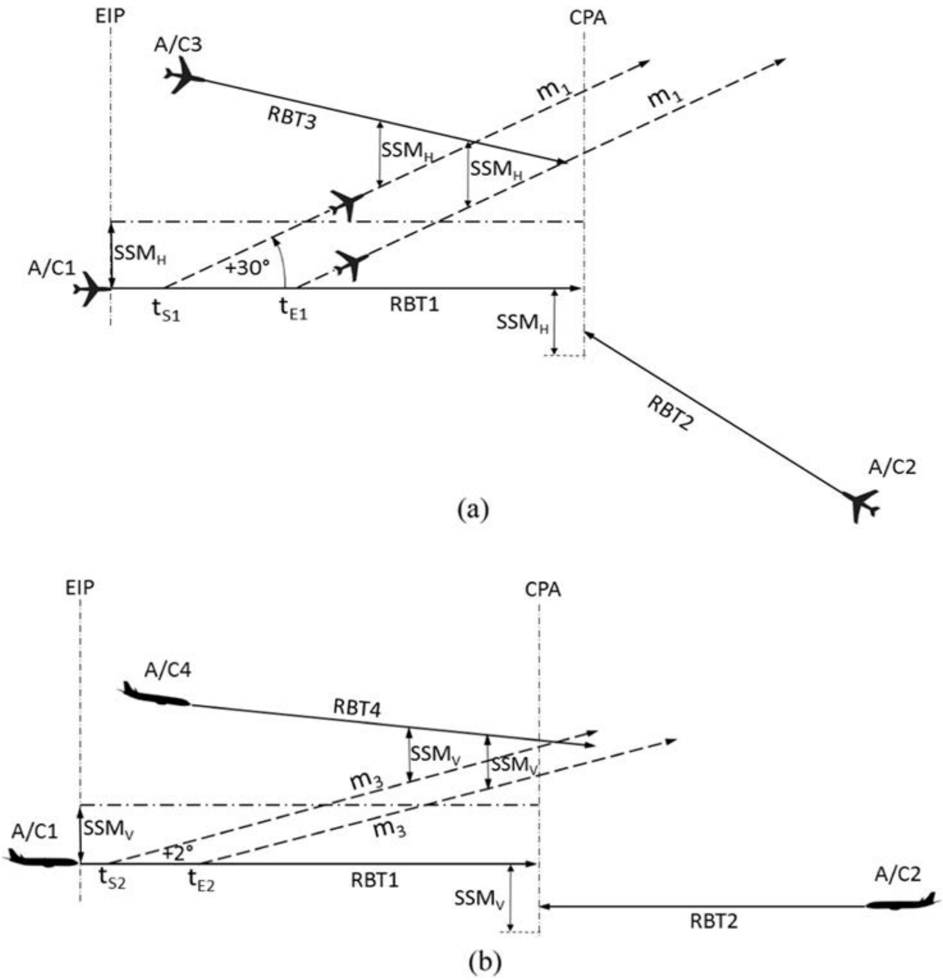

Fig. 8. Determination of the conflict subintervals generated from STIs in (a) horizontal plane, (b) vertical plane.

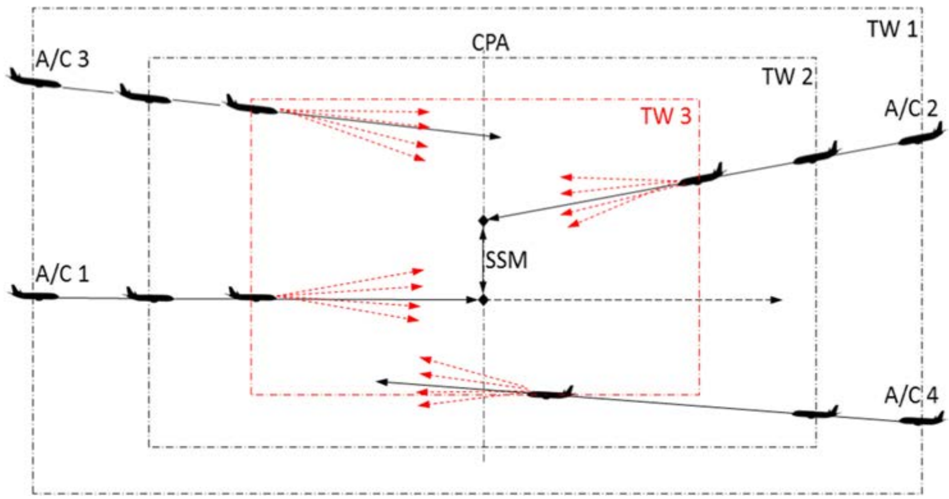

Fig. 9. Ecosystem evolution towards EDE.

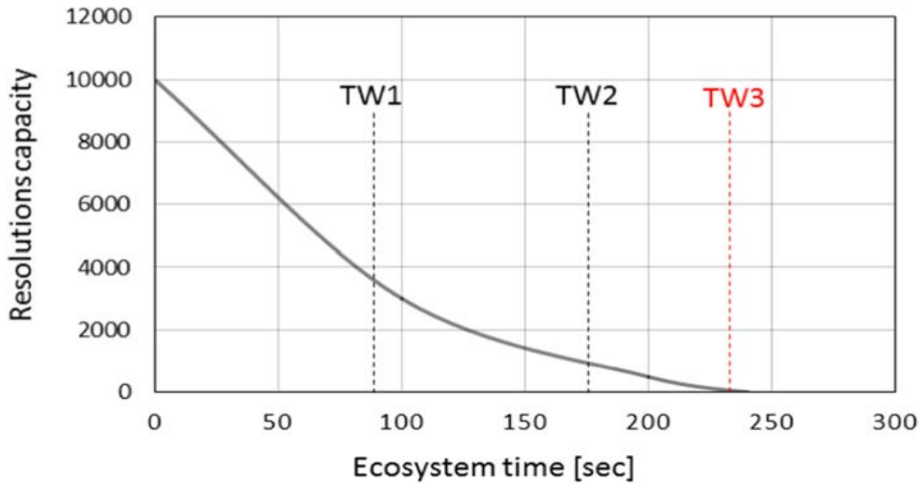

Fig. 10. Rate of change in the total number of avoidance maneuvers (resolution capacity).

TW2. The number of solutions approaches to zero value when the ecosystem enters TW3. Therefore, the total number of solutions at a certain moment can be defined as a resolution capacity of the ecosystem at that moment.

As noted from Table 2, an ecosystem solution is not possible at a time instant belonging to any of the conflict intervals. In other words, any time window in which no interdependency exists is treated as a potential solution interval. Therefore, it can be derived that a total number of ecosystem solutions at a random time instant **t**, $t \in [t_{EIP}, t_{CPA}\text{-}60)$, equals to a difference between a theoretical number of the ecosystem maneuvers and a total number of the conflict maneuvers, succeeding this instant, and provided that the maneuverability checks are performed with the constant time rate. t_{CPA}-60 presents a time instant shifted 60 s back from the closest point of approach timestamp. This is the latest moment at which the ecosystem deadlock event might occur, i.e. the number of the ecosystem solutions at that moment is 0. However, the ecosystem deadlock event might occur before t_{CPA}-60, depending on the factors previously explained. Thus, an ecosystem deadlock instant belongs to the interval $t_{ED} \in (t_{EIP}, t_{CPA}\text{- } 60]$.

The theoretical number of the ecosystem maneuvers (both conflict and conflict-free) is defined as:

$$TM_E(t) = \frac{1}{\tau} M^{Ne}(t_{CPA} - 60 - t) \tag{12}$$

where τ presents a checking time rate (1 s by default, but also user-configurable), and M is the number of types of the potential avoidance maneuvers. In this study $M = 5$, since there are five types of maneuvers, explained in Section 4.3. In addition, for $\forall t_{Sk} \in [t_{EIP}, t_{EDE})$, $\forall t_{Ek} \in (t_{EIP}, t_{EDE}]$, $t_{Sk} < t_{Ek}$, $k \in [1, I]$. I denote the total number of conflict intervals within one ecosystem. The number of conflict maneuvers generated due to interdependencies with surrounding aircraft is computed by:

$$C_E(t) = \frac{1}{\tau} M^{(Ne-2)} \sum_{k=1}^{I} [t_{Ek} - \max(t_{Sk}, t)] \tag{13}$$

where t_{Sk} and t_{Ek} are starting and ending time moments of each conflict sub-interval within the interdependencies structure (Table 2). Then, a difference between TM_E and C_E presents the number of the ecosystem solutions, or the resolution capacity counted from t:

$$S_A(t) = TM_E(t) - C_E(t) = \frac{1}{\tau} M^{(Ne-2)} (M^2(t_{CPA} - 60 - t) - \sum_{k=1}^{I} [t_{Ek} - \max(t_{Sk}, t)]) \tag{14}$$

The maximum number of solutions is obtained in a moment of the ecosystem identification, i.e. $t = t_{EIP}$:

$$S_A max = \frac{1}{\tau} M^{(Ne-2)} (M^2(t_{CPA} - 60 - t_{EIP}) - \sum_{k=1}^{I} [t_{Ek} - t_{Sk}]) \tag{15}$$

Since $\forall\ t_{Sk} \geq t_{EIP}$, the values of t_{Sk} are included in the summation. Finally, the deadlock event occurs when the number of the ecosystem solutions reaches 0, i.e. $S_A max = 0$:

$$(M^2(t_{CPA} - 60 - t_{ED}) - \sum_{k=1}^{I} [t_{Ek} - t_{ED}]) = 0 \tag{16}$$

Expression (16) computes the value of t_{DE} that corresponds to TW3, illustrated on Figs. 9 and 10. Fig. 11 illustrates an example of the ecosystem with three aircraft whose maximal number of solutions reaches 67,500 according to the discretization proposed in the moment of the ecosystem identification. t_{EDE} is reached 245 s after t_{EIP}.

During the ecosystem evolution, the resolution capacity can be maintained over certain subintervals, but can even be increased.

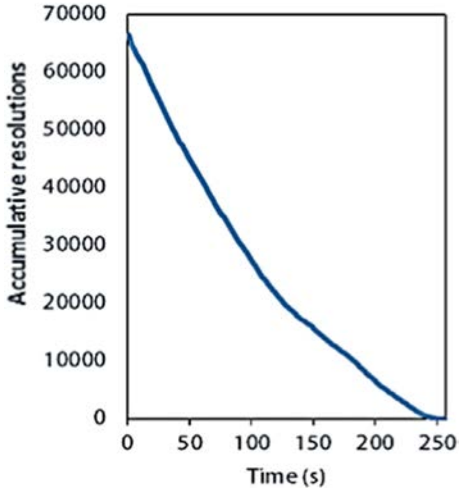

Fig. 11. Change in the accumulative resolutions over the ecosystem time.

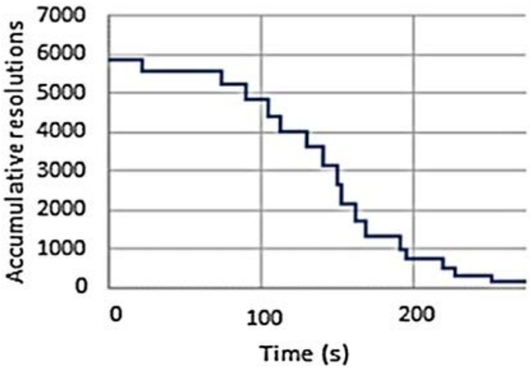

Fig. 12. Stepwise decreasing trend in the resolutions capacity over the ecosystem time.

As previously explained, it directly depends on the relative geometry among trajectories and the aircraft state information. For instance, Fig. 12 illustrates a resolutions capacity as a decreasing stepwise trend, with close to 6000 solutions obtained at the ecosystem identification moment. The example refers to the ecosystem of three aircraft with the mixed flight modes (cruise, climb and descent) over time. The factors, like relative geometry of a trajectory pair, closure rates, flight configuration (climb, cruise or descent), as well as the type of conflict (encounter vs. overtaking) influence the changes in STIs over time. The rate of change in the number of solutions, in this case, can be modeled as a step-wise function, showing that the maintained resolution capacity over subintervals denotes the same number of STIs among the aircraft whose state variables and the relative trajectories geometry are constant over these subintervals.

Another considered complexity measure is type of STIs: cooperative or non-cooperative avoidance manoeuvre. In many cases, it is sufficient that only one aircraft performs the avoidance manoeuvre to remove STI, while another one keeps its RBT segment with m_0. However, by approaching to the collision avoidance zone, the effects of the time and space compression usually force the cooperative manoeuvres among the pairs of aircraft. Cooperatively, the ecosystem solutions are treated as follows:

- Aircraft could perform the cooperative resolution maneuvers in the same moment only. Therefore, the resolution capacity at a certain timestamp is compressed.
- The resolution trajectories must be initiated by the avoidance maneuvers, explained in the previous subsection. Analysis of the ecosystem solutions using the maneuvering values, other than listed, is a subject to further research and out of scope in this paper.
- The resolution maneuvers are considered potential, as some of the them might be acceptable and other unacceptable by the aircraft. An acceptability of the maneuvers is not analysed since it fully depends on the airspace users' business models.

The algorithm cumulatively computes the resolution capacity by searching for the avoidance maneuvers that do not belong to any conflict subintervals. This quantitative search is done by simulation at one-second rate, from the ecosystem identification point until the closest point of approach. The lowest ecosystem complexity over time is always achieved by two determinants:

Table 3
The algorithms' time performances for the given traffic simulation.

Procedure	Runtime [seconds]
Input data reading & writing with space-time filtering	33.814979205
Sampling & conflict detection outputs	2154.802506643
Clustering outputs	2.235798564
Ecosystem identification outputs	1.507529491

(1) One STI contains only one conflict subinterval between the aircraft pair.
(2) One aircraft performs m_0 as a part of a maneuvering combination that generates this STI (apart from an initial conflict where the combination is $m_0 - m_0$).

5. Simulation results

This section illustrates the simulation results obtained using the historical traffic data from Demand Data Repository 2 (DDR2), owned and maintained by EUROCONTROL. Simulations were run on a PC with Windows 7 OS (64-bit), processor Intel(R) Core(TM) i5-5200U with a CPU clock of 2.20 GHz, and 8 GB of RAM memory. The codes were written and compiled in Java IDE (integrated development environment). The algorithms comprise several user-defined packages. The algorithms can be called from other programs through an application program interface and, also be executed from a command line. The modeling parameters are user-configurable providing possibility for a multi-level analysis.

Since the ecosystem identification is a stepwise process that includes larger set of functions and parameters, the computation time of algorithms depends on the input data size. Considering one full day of operations over ECAC region in the en-route airspace above FL245 (airspace class A), with more than 30,000 flights, the processing time (including data reading, writing and computation) takes around 30 min in average. Therefore, the simulation runs are usually performed for the busier traffic intervals with one-hour duration.

The input data are the 4D flight plans, in the so-called *so6.m1* data model (Wandelt & Sun 2015). The traffic scenario dated on 24th August 2017, was timely filtered between 08.00 and 09.00, and spatially by altitude, between FL245 and FL450. Table 3 provides information on the time performances for outputs in each step, i.e. the input data reading and writing including space-time filtering, sampling and conflict detection, clustering and ecosystem identification.

As it can be observed, the biggest resource for the algorithm processing goes to the trajectories sampling and conflict detection procedure since the spatiotemporal search function is handling with larger amount of data (filtered 4-D trajectories), especially in case of the so6 data format that comprises additional pieces of trajectory information. According to the steps described in Section 4, the algorithm was first sampling the filtered trajectories, and then detected all pairwise conflicts. From detected conflicts, the clusters and the ecosystems are generated in a total number less than the number of conflicts because some clusters are composed of two concurrent conflicts which in total makes them less than the total quantified conflict pattern. Table 4 outputs the overall quantities from the simulated traffic.

Table 5 provides some statictics on the conflict types verified in Network Strategic Tool (NEST), that is owned and maintained by Eurocontrol. Fig. 13 visualises an extraction from the mapped pairwise conflicts in NEST.

Fig. 14 outputs the cluster and ecosystem structure between FL245 and FL450, i.e. the number of the clusters/ecosystems per number of members. The maximum identified number of both the cluster and ecosystem members was 6. The chart on the figure also describes the cluster-ecosystem transitions. For instance, the number of ecosystems with 2 and 3 members was increased comparing to the number of clusters with the same membership sizes. This is the result of a decrement in the number of the ecosystems with 4, 5 and 6 members. The reason is that certain members in many clusters were not identified as the ecosystem members with respect to the previously explained metrics.

The previous part of Section 5 was analysed more at a macroscopic level, briefing on the performance characteristics of developed algorithms. Since all ecosystems are analysed independently from each other, the study does not assume any correlations among them. Nevertheless, very high number of ecosystems within one hour of operations over certain airspace would probably indicate the correlations (interdependencies) among them. After performing their resolutions and resuming to the original trajectories, while also absorbing the time delays in resolution (due to assumption of the speed maintenance), the two nearby ecosystems might induce a new ecosystem in a short time ahead. But, this study will be subject to the future research.

The rest of Section 5 will focus more on a microscopic aspect of the ecosystems by quantifying the trajectory interdependencies. The idea is to analyse the ecosystem resolutions capacity based on the time criticality. For this purpose, two ecosystems are randomly

Table 4
The overall quantities obtained from the simulated traffic.

Total number of flights in traffic simulation	Total number of trajectories after space-time filtering	Total number of detected pairwise conflicts	Total number of clusters/ ecosystems
36,095	4079	1076	724

Table 5
Statistics on the conflict types, verified in NEST.

Number of conflicts: 4079
Number of conflicts by type (%): Evolving/Evolving: 15.73 Evolving/Cruise: 40.43 Cruise/Cruise: 43.84
Parallel: 50.60 Opposite: 12.95 Crossing: 36.46
Evolving/Evolving Parallel: 10.88 Evolving/Evolving Opposite: 1.83 Evolving/Evolving Crossing: 3.02 Evolving/Cruise Parallel: 18.90 Evolving/Cruise Opposite: 8.90 Evolving/Cruise Crossing: 12.63 Cruise/Cruise Parallel: 20.81 Cruise/Cruise Opposite: 2.22 Cruise/Cruise Crossing: 20.81

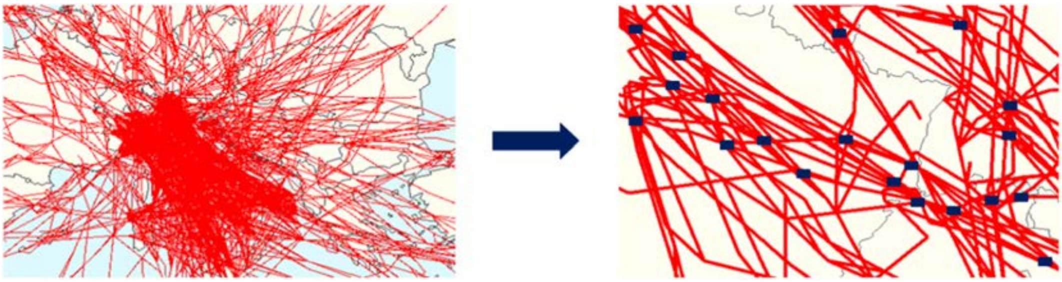

Fig. 13. Example of mapped pairwise conflicts; data validated and visualized in NEST.

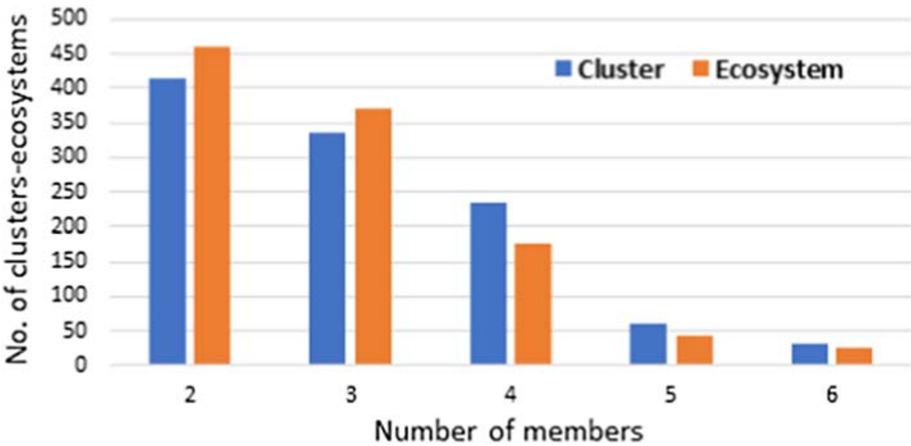

Fig. 14. Cluster-ecosystem transition from simulated traffic scenario between FL245 and FL450.

selected. Ecosystem 1 is composed of four aircraft while Ecosystem 2 contains five aircraft. Their data structures are presented in Tables 6 and 7, respectively.

The first index of the column Aircraft ID denotes the ecosystem number, and the second one the number of the aircraft within the ecosystem. For example, A/C23 presents Aircraft 3 belonging to Ecosystem 2. The aerial ecosystem creation function identifies all STIs for both ecosystem scenarios. The STI elements are provided in Tables 8 and 9, respectively.

Three STIs were identified inside Ecosystem 1, while in case of Ecosystem 2 there were four STIs. Simulations have shown that each STI comprised several conflict subintervals which points out to the complexity of both ecosystem scenarios. By analysing Ecosystem 1, it is evident that STI_1 presenting the interdependency between A/C11 and A/C12 does not provide sufficient capacity for the ecosystem removal, since search for the solution is spread out over the total ecosystem time. The manoeuvring combinations

Table 6
4D data inputs for Ecosystem 1.

Aircraft ID	φ [°]	λ [°]	h [ft]	t [s]
A/C11	48.000437	−3.542189	32,000	28950.00
	48.525643	−3.489133	32,000	29250.00
A/C12	48.046222	−3.874058	32,500	28950.00
	48.654123	−3.593567	33,000	29250.00
A/C13	48.221666	−4.334286	31,800	28950.00
	48.613478	−3.814290	32,000	29250.00
A/C14	48.710443	−4.075441	30,000	28950.00
	48.278766	−4.448257	33,000	29250.00

Table 7
4D data inputs for Ecosystem 2.

Aircraft ID	φ [°]	λ [°]	h [ft]	t [s]
A/C21	39.000067	−3.542189	36,000	29,159
	39.527825	−3.489133	36,000	29,459
A/C22	39.046234	−3.874058	36,000	29,159
	39.550689	−3.593567	36,000	29,459
A/C23	39.110918	−4.334286	36,000	29,159
	39.514274	−3.814290	36,000	29,459
A/C24	39.710338	−4.075441	39,000	29,159
	39.278833	−4.448257	39,000	29,459
A/C25	38.927724	−4.570034	36,000	29,159
	39.330255	−4.052782	36,000	29,459

Table 8
Generated STI structure for Ecosystem 1.

STI_ID	Interdependent aircraft IDs	Maneuvering combination	Conflict interval [seconds]
STI_1	A/C11–A/C12	m_0–m_0	28,950–29,152
	A/C11–A/C12	m_0–m_3	28,950–29,152
	A/C11–A/C12	m_1–m_2	29,035–29,146
	A/C11–A/C12	m_4–m_1	29,040–29,180
STI_2	A/C12–A/C13	m_0–m_1	29,020–29,130
	A/C12–A/C13	m_1–m_0	29,020–29,130
	A/C12–A/C13	m_3–m_0	28,950–29,135
STI_3	A/C11–A/C14	m_4–m_0	29,005–29,110
	A/C11–A/C14	m_4–m_3	29,027–29,115
	A/C11–A/C14	m_2–m_4	28,986–29,153

Table 9
Generated STI structure for Ecosystem 2.

STI_ID	Interdependent aircraft IDs	Maneuvering combination	Conflict interval [seconds]
STI_1	A/C21–A/C22	m_0–m_0	29,159–29,387
	A/C21–A/C22	m_0–m_3	29,159–29,387
	A/C21–A/C22	m_2–m_1	29,159–29,368
	A/C21–A/C22	m_3–m_2	29,188–29,387
	A/C21–A/C22	m_1–m_4	29,167–29,357
	A/C21–A/C22	m_4–m_3	29,231–29,368
STI_2	A/C22–A/C23	m_0–m_1	29,192–29,310
	A/C22–A/C23	m_0–m_4	29,192–29,310
	A/C22–A/C23	m_3–m_0	29,222–29,327
	A/C22–A/C23	m_3–m_3	29,232–29,310
STI_3	A/C21–A/C24	m_4–m_0	29,159–29,360
	A/C21–A/C24	m_1–m_2	29,165–29,345
	A/C21–A/C24	m_3–m_2	29,178–29,298
STI_4	A/C22–A/C25	m_2–m_0	29,279–29,289
	A/C22–A/C25	m_4–m_4	29,235–29,298
	A/C22–A/C25	m_3–m_3	29,249–29,253

Table 10
Potential non-cooperative avoidance maneuvers for Ecosystems 1 and 2.

Ecosystem ID	Aircraft ID	Avoidance maneuver	Conflict-free interval [sec]
Ecosystem 1	A/C11	m_4	28,950–29,004
Ecosystem 1	A/C12	m_1	28,950–29,019
Ecosystem 2	A/C21	m_3	29,159–29,177
Ecosystem 2	A/C22	m_2	29,159–29,187

are diverse, and either cooperative or non-cooperative avoidance manoeuvres out of the conflict subintervals would be the subject to potential induced conflict with A/C13 or A/C14. Therefore, the solution can be sought among STI_2 and STI_3. For potential overlaps between the conflict subintervals and non-cooperative manoeuvres (m_0 for one aircraft), one of the simplest and less complex situations would be provision of the m_4 manoeuvre to A/C11. In this case, a descent assigned to A/C1 at any moment within the interval [28950–29004] would resolve the ecosystem. Moreover, another utilized manoeuvre that could be applied is m_1 by assigning to A/C12. The conflict-free interval in which A/C12 could perform a left-heading change is [28950-29019].

In case of Ecosystem 2, three non-cooperative manoeuvres over different conflict intervals could facilitate the situation and provide “less expensive” ecosystem solution. The first manoeuvre could be m_3 assigned to A/C21 within [29159-29177], and the second one to A/C22 with m_2 over [29159-29187]. Table 10 illustrates the non-cooperative avoidance for the ecosystems solution.

Finally, Figs. 15 and 16 describe the time-based resolution capacity for Ecosystems 1 and 2, respectively.

Fig. 15 demonstrates how the number of solutions for the trajectories configuration within Ecosystem 1 could decrease, but also maintain and even increase at certain moments. That can be explained by a randomly distributed STI occurrences and overlaps of the conflict subintervals. Between 0 and 60 s of the ecosystem time, the resolution capacity is quite dynamic, and it decreases, increases, but also keeps the same number of solutions. At the 60-seconds stamp, there is a notably high loss in the overall capacity, and then further the gradual decrement in the solutions is again evident. Ecosystem 1 would reach zero solutions, i.e. the deadlock state after 210 s of the ecosystem time.

Fig. 16 describes more complex time-based resolution capacity. In this case, at certain moments the number of solutions even increases. In these moments there is more capacity for an efficient and inexpensive ecosystem resolution. A rapid drop in first 15 s and a continuous one after 115 s support the fact that conflict subintervals randomly overlap. Within these periods the cooperative manoeuvres are required to resolve and remove the ecosystem, which presents more *expensive* solution. After 200 s Ecosystem 2 would reach its deadlock state.

6. Conclusions and further research

This article elaborates the concept of aerial ecosystem, explaining its stepwise generation procedure. The main driver in this generation is the pairwise, state-based conflict detection algorithm and the metrics adopted to build the cluster volumes and causally identify the ecosystems. The aerial ecosystem framework has presented a baseline in the STI identification, expressing the structure of the conflict intervals as a combination of the potential conflict manoeuvres. The model has an ability to further explore the potential resolution capacity in the search space of the conflict-free manoeuvres. It is noteworthy to say that the concept is applications-oriented rather than a theory-based, developed with a quantitative and less conservative modelling approach, and customized to the current traffic queries and the operational environment. The simulation studies have shown a significance in providing the time capacity for a set of certain manoeuvres, at the operational level, when a severity of the conflict situation occurs very rapidly. A decreasing rate of the available ecosystem resources and an elapsed time describe a potential path in a thorough analysis of resolution dynamics, meaning that each missed moment in making a resolution agreement might induce less number of the conflict-free

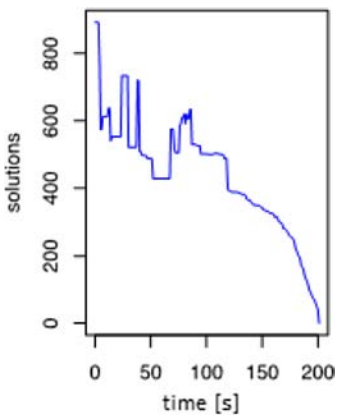

Fig. 15. Time-base solutions capacity for Ecosystem 1.

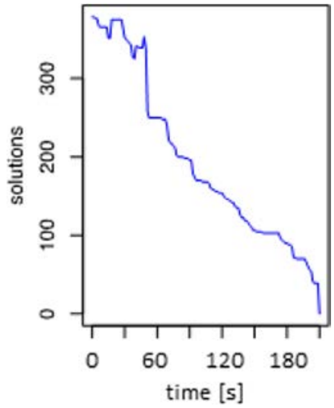

Fig. 16. Time-based solutions capacity for Ecosystem 2.

manoeuvres, but also maintain or increase them in some circumstances. The factors, like relative geometry of a trajectories, closure rates, flight configuration, as well as the type of conflict influence the changes in STIs over time. The results obtained through simulation and analysis of two ecosystems samples present one of the indicators for the emergent dynamics of induced conflicts, measuring the resolution capacity of the multi-aircraft systems in time evolution. With an increased ecosystem size, the STI structure becomes larger which produces less resolution capacity and a shorter ecosystem time.

The implemented algorithms provide a robust methodology for a future ATC-support development tool. However, the computational performances are currently limiting the tool being considered as the real-time decision support system. Further research is expected in three directions: analysis of multithread conflicts with respect to the time to CPA, decreasing the computational time of the stepwise algorithms concurrently by simulating the larger traffic samples, and extension of the cluster and ecosystem metrics for more robust interdependencies testing.

Acronyms	Meaning
4DT	Trajectory described in terms of 3 spatial dimensions and time stamps 4-dimensional trajectories
A/C	Aircraft
ADS-B	Automatic Dependent Surveillance – Broadcast
ALIM	Altitude Limitation
ATC	Air Traffic Control
ATM	Air Traffic Management
BADA	Base of Aircraft Data
CFL	Cleared Flight Level
CPA	Closest Point of Approach
DDR2	Demand and Data Repository 2
DMOD	Distance Modification
EIP	Ecosystem Identification Point
FL	Flight Level
GPS	Global Positioning System
IDE	Integrated Development Environment
LAT	Look-Ahead Time
MTCD	Medium Term Conflict Detection
NEST	Network Strategic Tool
NM	Nautical Mile
RA	Resolution Advisory
RBT	Reference Business Trajectory
RFL	Requested Flight Level
SL	Sensitivity Level
SSM	Standard Separation Minima
ST	Surrounding Traffic
STCA	Short Term Conflict Alert
STI	Spatiotemporal Interdependency
TA	Traffic Advisory
TBO	Trajectory-Based Operations
TCAS	Traffic alert and Collision Avoidance System

UAS	Unmanned Aerial System
WP	Waypoint
ZTHR	Z (altitude) Threshold

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4. Adaptive aerial ecosystem framework to support tactical conflict resolution

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Adaptive aerial ecosystem framework to support tactical conflict resolution

M. Radanovic, M.A. Piera and T. Koca
marko.radanovic@uab.cat
Department of Telecommunications and Systems Engineering
School of Engineering
Autonomous University of Barcelona
Sabadell
Spain

ABSTRACT

To support a seamless transition between safety net layers in air traffic management, this article examines an extra capacity in the generation of the resolution trajectories, conditioned by future high dense, complex surrounding air traffic scenarios. The aerial ecosystem framework consists of a set of aircraft services inside a digitalised airspace volume, in which amended trajectories could induce a set of safety events such as an induced collision. Those aircraft services strive to the formation of a cost-efficient airborne separation management by exploring the preferred resolutions and actively interacting with each other. This study focuses on the dynamic analysis of a decreasing rate in the number of available resolutions, as well as the ecosystem deadlock event from the identified spatiotemporal interdependencies among the ecosystem aircraft at the separation management level. A deadlock event is characterised by a time instant at which an induced collision could emerge as an effect of an ecosystem aircraft trajectory amendment. Through simulations of two generated ecosystems, extracted from a real traffic scenario, the paper illustrates the relevant properties inside the structure of the ecosystem interdependencies, demonstrates and discusses an available time capacity for the resolution process of the aerial ecosystem.

Keywords: Conflict detection; Aerial ecosystem; Resolution manoeuvres; Deadlock event

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NOMENCLATURE

3D	3-dimensional
4D	4-dimensional
alt	altitude
A/C	aircraft
ATC	air traffic control
ATFM	air traffic flow management
ATM	air traffic management
C_A	total number of the conflict manoeuvres
CA	collision avoidance
CD	conflict detection
CNS	communication, navigation and surveillance
CP	conflict point
CPA	closest point of approach
D	diameter of protected cylinder
DDR2	demand data repository 2
DST	decision support tool
ECAC	European Civil Aviation Conference
EDE	ecosystem deadlock event
ET	ecosystem time
FL	flight level
H	height of protected cylinder
I	number of conflict subintervals
lat	latitude
LAT	look-ahead time
long	longitude
m	type of manoeuvre
M	number of manoeuvres
MTCD	mid-term conflict detection
N_A	number of aircraft
N_{STI}	number of spatiotemporal interdependencies
NextGen	Next Generation Air Transportation System
PM	prediction moment
RBT	reference business trajectory
s	aircraft state position
S_A	total number of the ecosystem resolutions
ST	surrounding traffic
STCA	short-term conflict alert
STI	spatiotemporal interdependency
SESAR	Single European Sky ATM Research
SM	separation management
SSM	standard separation minima
t_{CP}	starting conflict moment
t_{DE}	deadlock event instant
t_{Ek}	ending moment of the *k*th conflict subinterval
t_{PM}	conflict prediction instant
t_{Sk}	starting moment of the *k*th conflict subinterval

TCAS	traffic-alert and collision avoidance system
TM_A	total manoeuvrability of the ecosystem aircraft
TW	time window
v	aircraft velocity vector
τ	checking time rate

1.0 INTRODUCTION

Trajectory deviations in high dense air traffic delimited volumes causes the separation minima infringements in many air traffic control (ATC) sectors. This reduction generates a complexity in the assigned traffic and increases the workload of air traffic controllers, especially at the tactical level[1]. As a response, several research and development concepts have been carried out to advance the Communication, Navigation and Surveillance/Air Traffic Management (CNS/ATM) technology and meet the principal attributes: safety, capacity and cost-efficiency of operations[2,3]. Based on SESAR (Single European Sky ATM Research) and NextGen (Next Generation Air Transportation System) initiatives[4,5], it is expected a replacement of the centralised ATC interventions by a distribution of separation management (SM) tasks, relying on advanced decision support tools (DSTs). This foresees important changes in the co-operation, situational awareness and functionalities of the overall ATM system[6].

When a loss of standard separation minima (SSM) between two aircraft occurs, they are considered being in a conflict. For en-route traffic, the SSM in the horizontal plane takes 5 nautical miles ($SSM_H = 5$ NM), while in the vertical plane, it is 1000 feet ($SSM_V = 1000$ ft). An important aspect of the tactical conflict detection (CD) algorithms is the prediction moment (PM), that is, a time instant at which the loss of separation is anticipated. Time measured from this moment until a moment at which two conflicting aircraft reach their closest point of approach (CPA) is denoted as the look-ahead time (LAT). CPA is an estimated 4D point at the aircraft trajectory, at which a 3D distance between two aircraft in conflict reaches its minimum value. Depending on the instant at which a separation minima infringement is predicted (starting conflict moment, t_{CP}), aircraft dynamics and trajectory geometries, the predicted pairwise encounter can be properly handled by an ATC directive, such as speed, heading or altitude change. In Ref. 7, it is reported how major changes in the active aircraft manoeuvrability could potentially induce successive conflicts with neighbouring aircraft and pull them in collision avoidance (CA). CA is the last safety net layer[8], which is fired because the conflicting aircraft following their trajectories, or performing any feasible manoeuvre, would not preserve the SSM. In these situations, the aircraft separation falls for other safety requirements and is delegated to the safety systems on-board aircraft[9]. One of such systems is Traffic alert and Collision Avoidance System (TCAS). TCAS, as an airborne autonomous system, demonstrates excellent performances for pairwise aircraft encounters but, unfortunately, suffers from a lack of a performance logic owing to well-reported induced collisions from the surrounding traffic scenarios[10]. Moreover, TCAS resolution advisories are frequently opposite from the ATC procedures and could create a lack of integration between the SM layer at the tactical level, and the CA layer at the operational level[11]. Thus, new research concepts relating a coherent integration of the full safety net are essential.

The aerial ecosystem framework relies on the analysis of spatiotemporal interdependencies between aircraft located in the surrounding traffic of a pairwise conflict that will lead to a trajectory amendment. By checking the manoeuvrability impact of any aircraft that could be affected by a pairwise conflict resolution, it is possible to predict an operationally emergent behaviour of the surrounding traffic and identify a subset of the trajectory amendments that will not cause a negative domino effect with neighbouring aircraft. At a technological level, the proposed ecosystem concept[12] relies on multi-agent technology[13,14], in which agents represent a set of aircraft inside a computed airspace volume, with a trajectory-amendment decision-making capability, whose trajectories are causally involved in the safety event. Each time a conflict is detected, an aerial ecosystem is initialised with the aircraft involved in a pairwise conflict, and it engages all the surrounding aircraft whose trajectory segments could be affected by a trajectory amendment of a conflict aircraft during the LAT. The set of spatiotemporal interdependencies (STIs) between ecosystem aircraft is analysed in this paper to evaluate the extra capacity to support a seamless transition between the SM and CA safety layers. The STI identification is computed timely in advance by applying the proper operational metrics at specific time instances, preceding the conflict event. The concept supports the trajectory-based operations by discretisation of the 4D trajectories and considers an operational environment in the en-route airspace, above FL245, within a LAT of 300 s. Figure 1 illustrates an example of the ecosystem creation where A/C1 and A/C2, being in predicted conflict, identify the surrounding traffic (ST) aircraft, namely A/C3 and A/C4, by applying certain avoidance manoeuvers, m_2 and m_4 (the manoeuver types are further explained in Section 3).

The ecosystem services enhance co-operative aircraft interactions and resolution decisions before the conflict evolves into an ecosystem deadlock event (EDE)[15,16]. This event is characterised by a time instant at which an induced collision could emerge as an effect of a trajectory amendment. EDE depends on the geometric profiles of the ecosystem trajectories, the aircraft closure rates and performances. A time frame between the ecosystem creation moment and the EDE instant is used by the ecosystem members to negotiate their conflict resolutions. This negotiation could be implemented by the multi-agent ontology framework[17], in which each aircraft is enhanced by a self-governed capability to follow its own

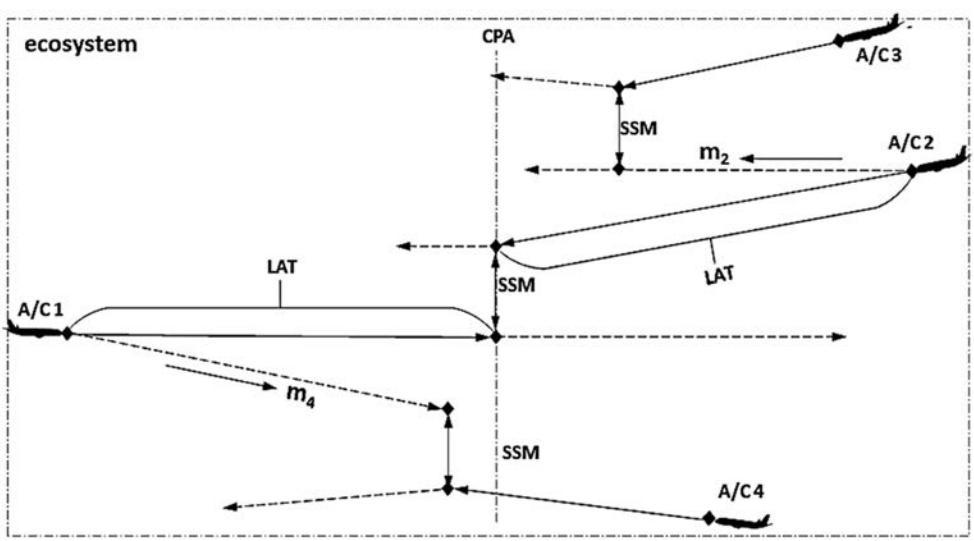

Figure 1. Ecosystem creation.

performance model to identify a preferred resolution. This technology provides right support in the negotiation interactions, aiming to reach a timely resolutions consensus and avoiding the ATC intervention before EDE, which does not consider the airspace users' preferences.

Developed ecosystem algorithms provide a robust methodology and the functionalities, intended as an integrated ATC-supporting tool. The tool is to be operable in the en-route airspace, at the tactical level, for a relatively short-time separation provision. The main outcomes for ATC are the computation of compulsory resolutions at the different ecosystem timestamps, a loose measure of the complexity of the ecosystem and a set of feasible resolutions that could be shared with the airspace users involved in the ecosystem for ranking preferences.

This article examines an extra capacity in the generation of the resolution trajectories when a time criticality is threatening the decision-making ability of the ecosystem aircraft. This criticality is expressed by the ecosystem EDE that differently occurs in the traffic scenarios with different complexities. The complexity of those scenarios is based on the concept of aerial ecosystems. At a tactical level, an aerial ecosystem presents a set of aircraft, having an autonomous decision-making capability, that are flying inside certain airspace volume, whose trajectories are causally involved in the safety event-detected conflict. Those aircraft strive to the formation of a cost-efficient separation management by exploring the preferred resolutions and actively interacting with each other. This study focuses on computation of a decreasing rate in the amount of potential resolutions as well as EDE from the identified STIs among trajectories. EDE is characterised by a time instant at which at a total number of the ecosystem solutions takes the zero value. Through simulations of two generated ecosystem, extracted from a real traffic scenario, the paper illustrates the relevant properties inside the structure of the ecosystem interdependencies and discusses an available time capacity in the resolutions process of the ecosystem aircraft. The simulation cases of two ecosystems extracted from a real traffic scenario have been conducted and analysis of the potential resolutions capacity has shown some operational aspects, but also the limitations. These limitations will be subject to further research steps through the implementation of the multi-agent systems ontology, as a significant enabler.

In addition to this introductory section, the paper comprises additional four sections. Section 2 is dedicated to the problem definition. Section 3 describes the computational framework for identification of the STIs from the ecosystem creation algorithm and analytical model for a potential resolution capacity (decreasing rate in the number of potential resolutions) and the EDE. Section 4 discusses the simulation results and comments on the time capacity for both ecosystems, while the concluding remarks and directions for the follow-up research are given in Section 5.

2.0 PROBLEM DEFINITION

This section illustrates two key aspects of the conflict resolution analysis in the complex traffic environments. Their justification requires the new quantitative methods to enhance present safety nets.

2.1 Conflict interval for the pairwise encounter

The tactical level within air traffic flow management (ATFM) is timely framed between two ATC thresholds: mid-term conflict detection (MTCD), that activates approximately 15 min before the closest point of approach (CPA) between two aircraft, and short-term conflict alert (STCA), that is triggered around 120 s before the CPA[(18)]. After STCA, two aircraft in conflict could potentially enter a CA layer that is characterised by a non-ATC separation provision, but an autonomous airborne safety system, such as TCAS[19]. Therefore, new research lines are required towards the development of the collaborative and decentralised tactical aerial system, on which both human behaviour and automation will be fully aligned. That envisages an operational integration of the safety procedures in such a way that any pair of aircraft involved in a conflict, together with surrounding aircraft, behave as a stable conflict-free air traffic system. Furthermore, the integration should be characterised with the critical information on the feasible resolution trajectories proposed through the development of the airborne and ground-based DSTs[20].

Figure 2 describes the conflict process between two aircraft, projected in the horizontal and vertical plane. The conflict between aircraft A/C1 and A/C2 (Fig. 2(a)) starts when they reach

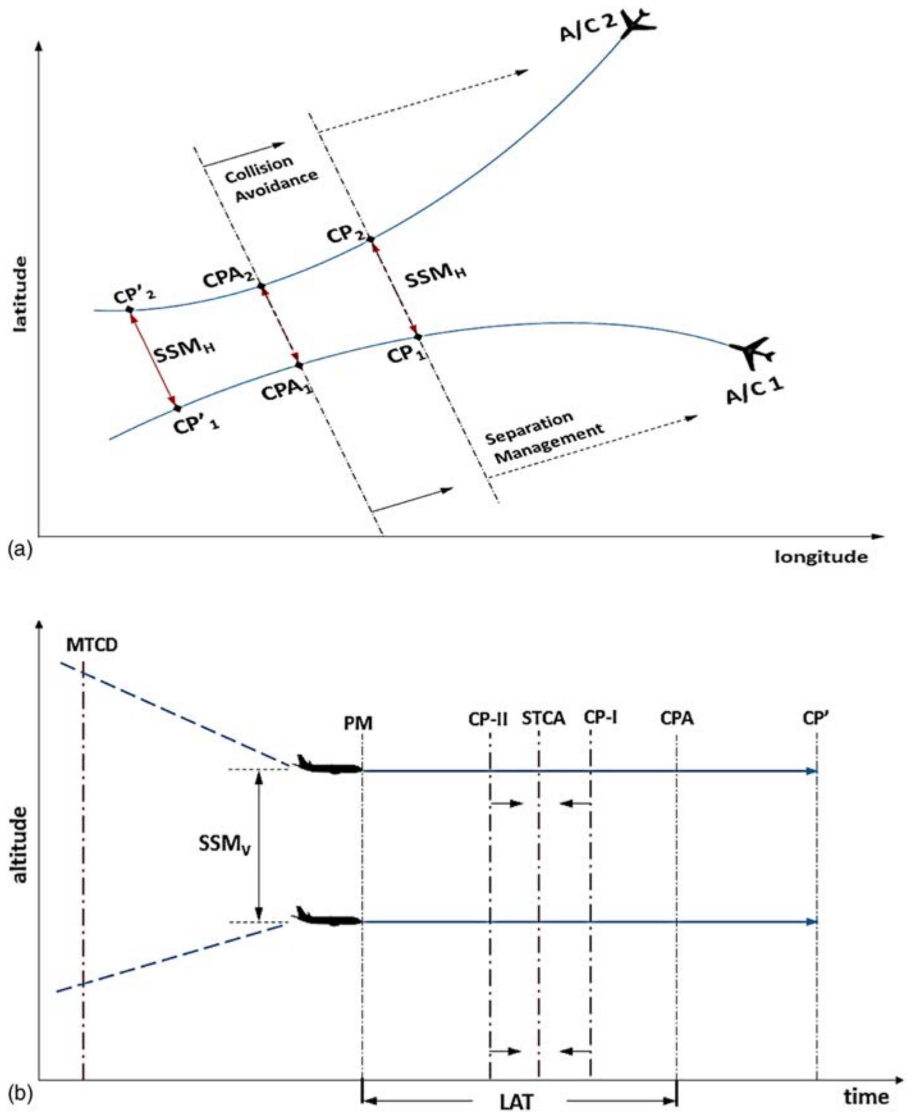

Figure 2. (Colour online) Conflict process for pairwise encounter; transition from SM to CA.

the waypoints CP_1 and CP_2, and ends when fly over CP'_1 and CP'_2, respectively. At CPA_1 and CPA_2, the aircraft come to the shortest conflict distance. The starting conflict moment is approximately close to the STCA threshold. In most cases, it is detected after STCA (CP-I), but it can also occur before (CP-II) when the closure rates are lower and the geometric configuration of trajectories is more complex. Detection of this moment is essential for coherent transition from separation management to collision avoidance. The conflict interval ends up at CP' (Fig. 2(b)). A very frequent case in a geometry of the aircraft encounters is that a CPA instant presents also the starting conflict moment (Fig. 3). In this case, PM is advanced 300 s before the beginning of the conflict.

Therefore, a proper detection of the conflict interval, for the pairwise encounter, is essential for the ecosystem conflict management. The starting conflict instant must be a referent moment from which the EDE instant can be computed, depending on the complexity of the

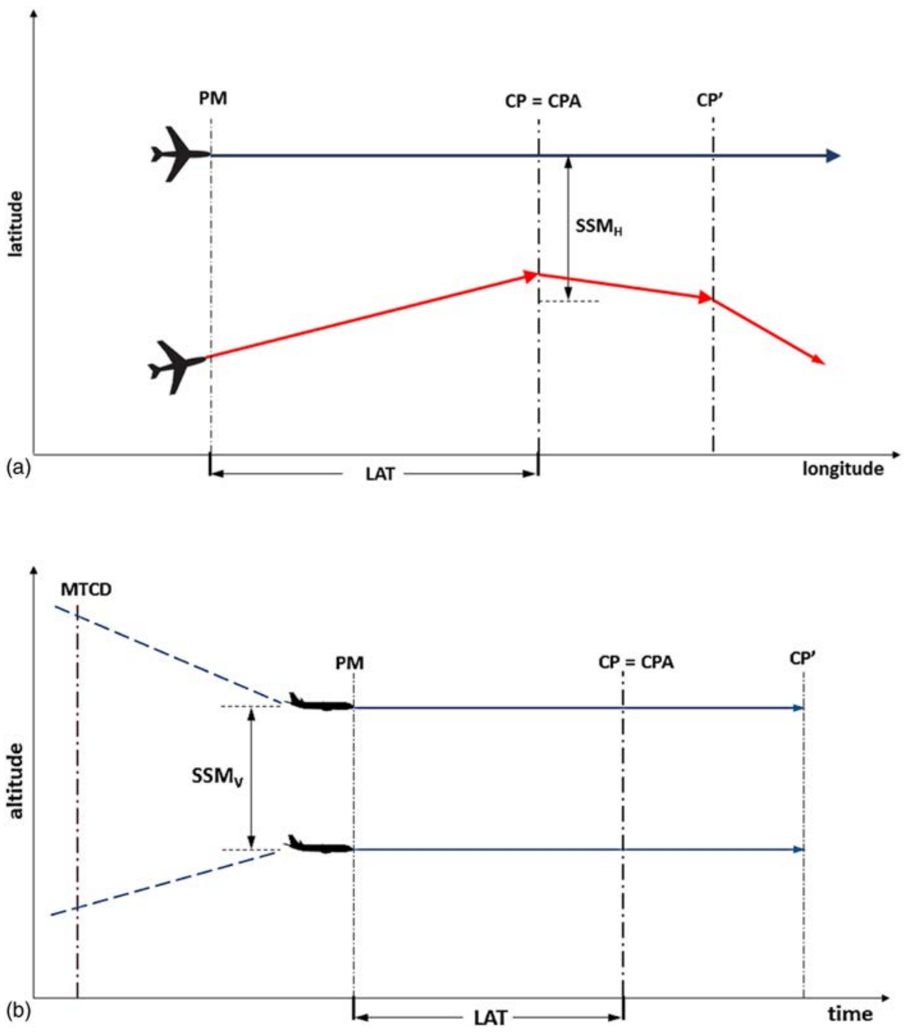

Figure 3. (Colour online) The conflict interval where the CPA and CP moments overlap.

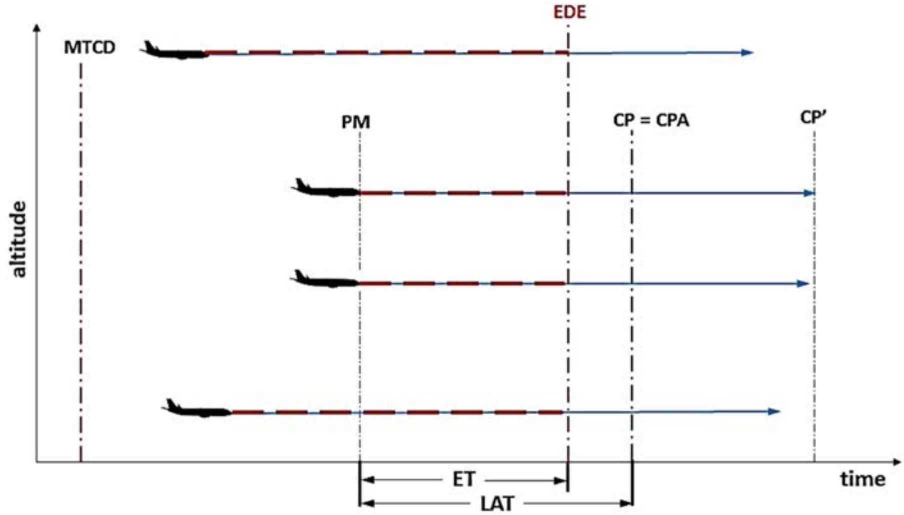

Figure 4. (Colour online) EDE positioning within the LAT and ET determination.

ecosystem scenario, i.e. the number of aircraft and a geometry of their trajectories (Fig. 4). In this sense, the ecosystem life time (ET) is defined as time difference between EDE and PM. A longer LAT provides an extra time for the analysis of all STIs and enhances a co-ordinated set of conflict resolution manoeuvers; however, it also increases considerably the uncertainty in the trajectories and the amount of unnecessary ecosystem members. On the other hand, a reduction of the LAT could drastically affect the safety of planned operations. Thus, a LAT of 300 s allows the use of aircraft state variable information to represent the ecosystem trajectories by segments with a low uncertainty.

2.2 Ecosystem evolution and deadlock event

The ecosystem evolution towards a determined EDE is characterised by a continuously decreasing rate in the number of potential resolutions that could be applied during the ecosystem life time. Figure 5 illustrates the ecosystem evolution in the vertical plane over three time-windows, TW1, TW2 and TW3. Each subsequent window is a sub-window of the previous one. TW3 denotes a CA window whose edges present the EDE moment. Aircraft reaching this ecosystem window on their Reference Business Trajectories (RBTs) would not be subject to the ATC separation provision, but the TCAS activation. Therefore, any co-ordinated (co-operative) manoeuvers of the aircraft that would provide a conflict-free ecosystem resolution, with respect to the SSM, must be performed before entering TW3.

Figure 6 shows a theoretical decreasing rate in a number of the conflict-free solutions, denoted with $S(t)$, over the LAT. The values for $S(t)$ have been taken as an example to illustrate a higher drop in the amount of solutions occurring until the TW1, and then follow-up with lower decreasing rate until the TW2. $S(t)$ is approaching to the value “0” when the ecosystem enters the TW3. The time threshold for entering TW3 presents a CP instant for a detected pairwise conflict. In most cases, their order of magnitude is higher, that depends on the manoeuverability discretisation supported by the technology, the ecosystem size (the number of involved aircraft) and the STI structure among the trajectory segments.

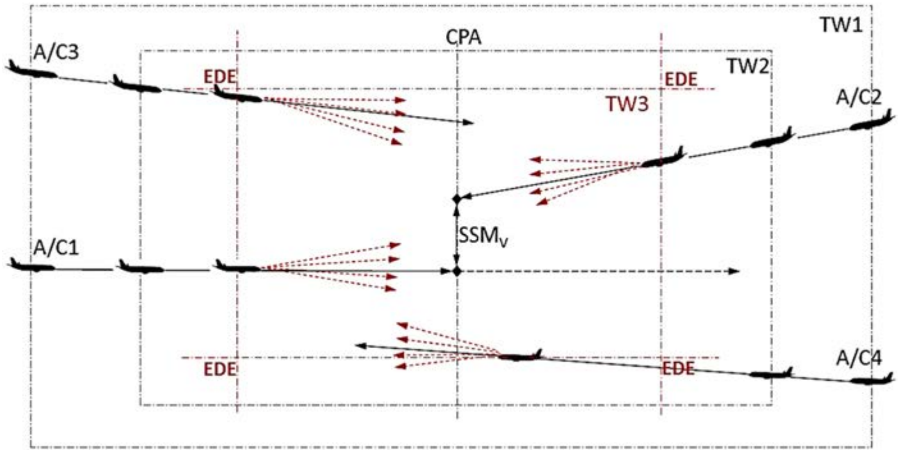

Figure 5. (Colour online) Ecosystem evolution towards EDE.

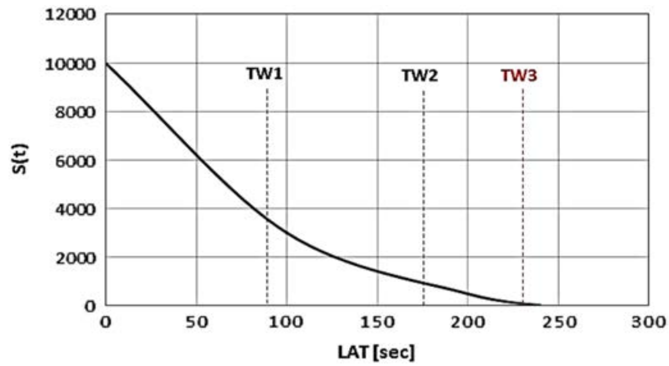

Figure 6. (Colour online) Rate of change in the number of resolutions.

3.0 COMPUTATIONAL FRAMEWORK

This section describes the procedure for the STI identification and its utilisation on the analytical computation of the EDE. A short reference to the ecosystem generation has been provided with an aim at introducing the manoeuverability criteria that could be maintained for the resolutions generation.

3.1 State-based CD and ecosystem creation

For computation of the starting conflict moment, t_{CP}, there has been implemented a Eucledean state-based CD algorithm. As developed in Ref. 21, the algorithm simplifies the methodology referring to the case of two aircraft in conflict, A and B. Their states can be described by positions s_A and s_B, and their velocity vectors by v_A and v_B, respectively. Projections of the aircraft A position along axes are denoted with s_{Ax}, s_{Ay} and s_{Az}, while projections of its velocity vector are marked with v_{Ax}, v_{Ay} and v_{Az}, respectively. Each aircraft is surrounded by an imaginary volume called the protected zone. It defines a minimum separation distance between aircraft. The protected zone in a 3D space takes a shape of a flat cylinder with diameter D and height H. Therefore, the imaginary cylinder around the aircraft A is defined by the set of points (x, y, z) satisfying the conditions:

$$\sqrt{(x - s_{Ax})^2 + (y - s_{Ay})^2} < \frac{D}{2} \qquad ...(1)$$

$$|z - s_{Az}| < \frac{H}{2} \qquad ...(2)$$

The minimal separation distance is considered here as SSM, which means: $SSM_H = \frac{D}{2} = 5$ NM, and $SSM_V = \frac{H}{2} = 1000$ ft. In a general context, the protected zone of the aircraft A is defined as a set of points, P_A, that satisfy

$$P_A = \left\{ x \middle| \|s_A - x\| < \frac{1}{2} \right\} \qquad ...(3)$$

where $\|.\|$ denotes a norm vector. In the case of the cylinder of diameter D and height H, the norm is defined as

$$\|(x, y, z)\| = \max\left(\frac{\sqrt{x^2 + y^2}}{D}, \frac{|z|}{H} \right) \qquad ...(4)$$

Using a norm expression, it can be defined as a distance between aircraft and, as a result, a loss of the SSM. The distance between the aircraft A and B is defined as

$$\Delta(A, B) = \| s_A - s_B \| \qquad ...(5)$$

A and B are in loss of separation if and only if Δ (A, B) < 1. One of the assumptions for the ecosystem creation is a linearity. At the future time instant: t, the state prediction A(t) from the current position can be expressed as

$$s_A(t) = s_A + t v_A \qquad ...(6)$$

$$v_A(t) = v_A \qquad ...(7)$$

CD is a predicted loss of separation between aircraft A and B within LAT. A and B are in conflict if there is a predicted instant t_{CP}, at which an achieved distance between the aircraft will be less than 1:

$$\Delta(A(t_{CP}), B(t_{CP})) < 1 \qquad ...(8)$$

Once the conflicts are detected, duration of the conflict intervals is checked by sampling the trajectories with 1-s rate, and comparing the shortest distances between the points of two trajectories at each instant with the SSM criteria (SSM_H and SSM_V). When the inter-distance exceeds either SSM_H or SSM_V (or both) the conflict interval ends in the moment t_{CP} The ecosystem creation procedure has been elaborated in Refs 12 and 22. This algorithm determines all cluster members as surrounding traffic aircraft for which the loss of SSM with any of two conflicting aircraft would occur if this aircraft performs a given avoidance manoeuver at any moment during LAT (Fig. 1). Considerably, the ecosystem creation is a spatiotemporal category as the applied manoeuver generates conflict subintervals with the surrounding aircraft. Manoeuverability is applied in both horizontal and vertical planes (Fig. 7) using a certain set of parametric values to identify those surrounding traffic aircraft that should be considered ecosystem members:

- $\mathbf{m_1}$: left heading change with a deflection angle of +30°;
- $\mathbf{m_2}$: right heading change with a deflection angle of –30°;
- $\mathbf{m_3}$: climb at a vertical rate of +1000 ft/min, and a flight path angle of +2°;
- $\mathbf{m_4}$: descent at a vertical rate of –1000 ft/min, and a flight path angle of –2°.

3.2 STI identification and EDE computation

The STI identification refers to the computation of the time windows for each ecosystem aircraft, inside which any potential co-operative or non-co-operative, horizontal or vertical, manoeuver could produce a loss of the SSM. Those windows are subintervals of LAT and the total number of conflict manoeuvers within each window is obtained as per defined time rate (by default, 1 s) along each RBT segment. Figure 8 shows an example of the conflict sub-interval generated using left heading change. Conflict subinterval no. 1 (CI1) denotes the period in which A/C1 performing a given manoeuver generates continuous conflict with A/C3.

The number of STIs (N_{STI}) between pairs of aircraft is obtained using four types of avoidance manoeuvers, explained above ($\mathbf{m_1}$, $\mathbf{m_2}$, $\mathbf{m_3}$ and $\mathbf{m_4}$), and one additional, $\mathbf{m_0}$: RBT follow-up. $\mathbf{m_0}$ means that an aircraft decides to continue flying over its RBT in a given moment. In this study, therefore, five types of manoeuvers are counted for, i.e., $M = 5$.

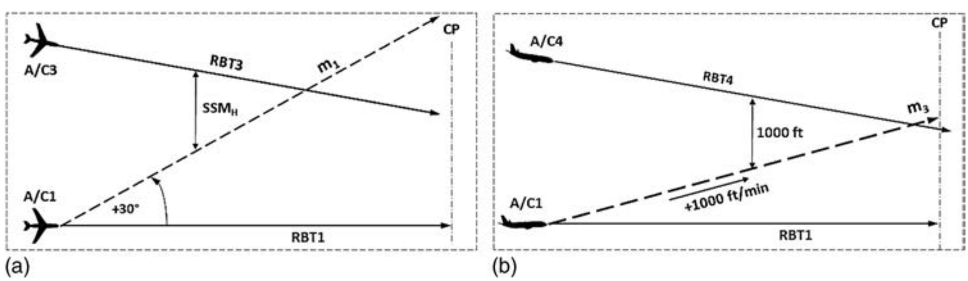

Figure 7. Identification of two ST aircraft; (a) A/C3 by left heading manoeuver of A/C1 and (b) A/C4 by climb amendment of A/C1.

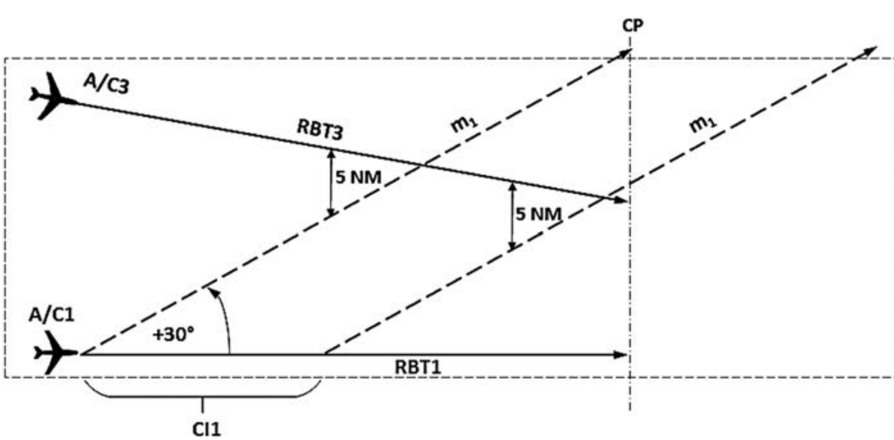

Figure 8. Conflict subinterval for a single RBT applying a deflection angle of +30°.

Table 1
Example of the STI structure

STI_ID	Interdependent aircraft IDs	Manoeuvering combination	Conflict subinterval (s)
STI_1	A/C1–A/C2	$\mathbf{m_0}$–$\mathbf{m_0}$	t_{S1}–t_{E1}
STI_2	A/C1–A/C3	$\mathbf{m_2}$–$\mathbf{m_2}$	t_{S2}–t_{E2}
STI_3	A/C2–A/C3	$\mathbf{m_1}$–$\mathbf{m_2}$	t_{S3}–t_{E3}

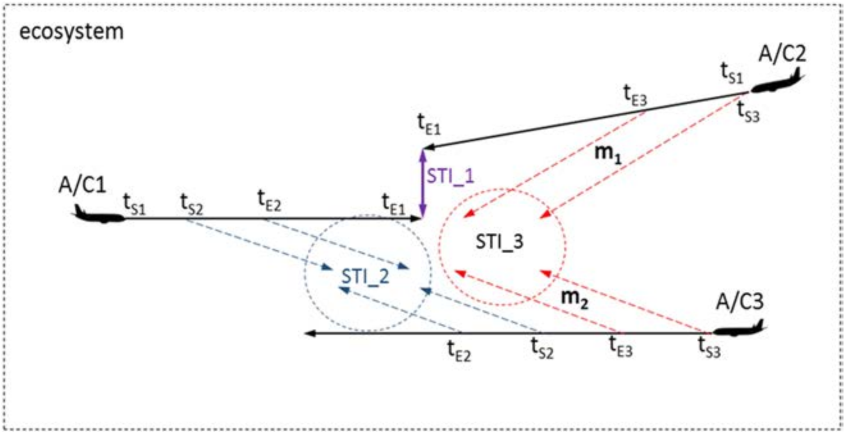

Figure 9. (Colour online) Spatiotemporal interdependencies for the given ecosystem with three members.

However, further research might introduce more manoeuvers (i.e., holding turns, regulated speed modifications among others) in the analysis. Each interdependency contains one or more conflict subintervals, and a total number of the conflict subintervals (I) within one ecosystem must satisfy the following condition:

$$I \leq \frac{N_A(N_A - 1)}{2} M^2 \qquad ...(9)$$

N_A denotes the number of ecosystem members, and M^2 is a derived property that presents the total number of manoeuvering combinations applied to one pair of aircraft. An example of the STI structure is presented in Table 1. It consists of the STI identifier, a combination of two interdependent flight identifiers, manoeuvering combination and conflict subinterval. t_{Sk} presents the starting instant of the conflict subinterval k for a pair of the ecosystem aircraft, while t_{Ek} denotes the ending moment, $t_{Sk} < t_{Ek}$, $k \in [1, I]$. One STI for one aircraft pair might have more conflict subintervals generated due to different manoeuvering combinations. Figure 9 illustrates an ecosystem example described in Table 1.

From Fig. 4, it can be expressed LAT and ET

$$\mathrm{LAT} = t_{CP} - t_{PM} \qquad ...(10)$$

$$\mathrm{ET} = t_{DE} - t_{PM} \qquad ...(11)$$

where t_{CP}, t_{PM} and t_{DE} present timestamps of predicted pairwise conflict, prediction moment and deadlock, respectively. With an objective to compute t_{DE}, in this study, the ecosystem solutions are treated as three-fold:

1. Co-operative mechanism: All aircraft involved in an ecosystem resolution amendment should initialise the manoeuver at the same time instant. Therefore, the resolution capacity at a certain timestamp, and in terms of the available time until the system deadlock, is compressed.
2. The resolution manoeuvers must correspond to the avoidance manoeuvers (Table 1) with a certain discretisation of the heading and vertical rate. Analysis of the ecosystem solution with a spectrum of the manoeuvering values is out of scope in this paper. The computation of the deadlock event would require a more thorough state-space-search technique.
3. The resolution manoeuvers are considered potential, as some of them might be acceptable and other unacceptable by the airspace user. The paper only analyses a potential time-space capacity for resolutions, and the acceptability is not considered since it highly depends on the airspace users' business models.

Nevertheless, the STI algorithm outputs the ecosystem conflict structure for each interdependency, meaning that an ecosystem solution is not possible at a time instant belonging to any of the conflict subintervals. In other words, any time window in which no interdependency exists is treated as a potential solution interval. Therefore, it can be concluded that a total number of ecosystem resolutions from the given time instant t, $t \in [t_{PM}, t_{CP})$, to t_{DE} equals to a difference between a theoretical number of the ecosystem manoeuvers and a total number of the conflict manoeuvers, succeeding this instant, provided that the manoeuverability checks are performed with the constant time rate. Therefore, the theoretical number of the ecosystem manoeuvers is defined as

$$\mathrm{TM}_{\mathrm{A}}(t) = \frac{M^{N_{\mathrm{A}}}}{\tau}(t_{\mathrm{CP}} - t) \quad \text{...(12)}$$

where τ presents checking time rate (1 s, by default). In addition, for $\forall t_{\mathrm{Sk}} \in [t_{\mathrm{PM}}, t_{\mathrm{CP}})$, $\forall t_{\mathrm{Ek}} \in (t_{\mathrm{PM}}, t_{\mathrm{CP}}]$, a conservative bound of conflict manoeuvers that cannot be flown due to STIs with surrounding aircraft is computed as

$$C_{\mathrm{A}}(t) = \frac{M^{(N_{\mathrm{A}}-2)}}{\tau}\sum_{k=1}^{I}\left[t_{\mathrm{Ek}} - \max(t_{\mathrm{Sk}}, t)\right] \quad \text{...(13)}$$

and the number of potential ecosystem resolutions

$$S_{\mathrm{A}}(t) = \mathrm{TM}_{\mathrm{A}}(t) - C_{\mathrm{A}}(t) = \frac{M^{(N_{\mathrm{A}}-2)}}{\tau}\left(M^2(t_{\mathrm{CP}} - t) - \sum_{k=1}^{I}\left[t_{\mathrm{Ek}} - \max(t_{\mathrm{Sk}}, t)\right]\right) \quad \text{...(14)}$$

The maximum number of solutions is obtained in the moment of the ecosystem creation, i.e. $t = t_{\mathrm{PM}}$

$$S_{\mathrm{Amax}} = \frac{M^{(N_{\mathrm{A}}-2)}}{\tau}\left(M^2(t_{\mathrm{CP}} - t_{\mathrm{PM}}) - \sum_{k=1}^{I}\left[t_{\mathrm{Ek}} - t_{\mathrm{PM}}\right]\right) \quad \text{...(15)}$$

$S_{\mathrm{A}}(t)$ is characterised by a decreasing rate in the time evolution. Finally, the deadlock event occurs when the number of the ecosystem solutions reaches the 0-value, i.e., $S(t) = 0$:

$$M^2(t_{\mathrm{CP}} - t_{\mathrm{DE}}) - \sum_{k=1}^{I}\left[t_{\mathrm{Ek}} - t_{\mathrm{DE}}\right] = 0 \quad \text{...(16)}$$

Expression (16) computes the value of t_{DE} that corresponds to TW3, illustrated in Figs 5 and 6.

4.0 ANALYSIS OF SIMULATION RESULTS

This section provides relevant results obtained from simulations of two ecosystems. The traffic scenario used for this purpose was DDR2,[1] s06.m1 model that comprises 4D flight plans[(23)]. The analysed traffic was dated on 24/08/2017 within the ECAC (European Civil Aviation Conference) airspace, with the total number of 36,095 flights during the day. Then, a traffic scenario was created by extracting of this traffic volume over the time interval 16:00–19:00, and filtering by altitude, above FL245 (the en-route airspace). The scenario counted for 9,698 flights.

From the traffic simulation, 2,237 pairwise conflicts have been identified, and two of them have been selected for analysis of the ecosystem creation and resolutions generation. The first ecosystem consists of three aircraft, while the second one was composed of four. Tables 2 and 3 provide the structure of the trajectory segments for the aircraft inside both ecosystems (for simplicity, instead of the flight identifiers – digits – there has been used an abbreviation "A/C#"). The abbreviations "lat","long" and "alt" present 3D spatial co-ordinates: latitude, longitude and altitude, respectively. The index "1" denotes the co-ordinates of the first 4D point, while "2" express the second one. Latitude and longitude are expressed in decimal degrees, altitude in feets and time in seconds. The time values are given in the accumulated seconds counted from the beginning of day.

For a better understanding of computation of the number of resolutions, the timestamps are converted to LAT interval (300-s-periods), taking

- time-1 = t_{PM} = 0 s – for both ecosystems,
- time-2 = t_{CP} = 298.00 s – Ecosystem 1,
- time-2 = t_{CP} = 218.49 s – Ecosystem 2.

Figures 10 and 11 (a, b and c) graphically describe the ecosystems in 3D (latitude–longitude–altitude) and 2D projections (longitude–latitude and time–altitude).

The simulation runs have output the main properties related to the STI structure (Table 4) while Figure 12 describes the potential resolution capacity for Ecosystems 1 and 2.

Looking at the values in Table 4, it can be observed that Ecosystem 1 (Ecosystem ID column) with three aircraft (N_A column) generated three interdependencies (N_{STI} column), while Ecosystem 2 with four aircraft generated four interdependencies. The interdependencies within Ecosystem 1 produced 19 conflict subintervals in total (I column), while in the case of Ecosystem 2 there were 33. The maximum number of solutions in the moment of Ecosystem 1 creation is 20,990 (S_{Amax} column), and, in the case of Ecosystem 2 creation, this number goes to 50,291 that initially provides more resolution capacity to Ecosystem 2. However, due to a significantly higher number of the conflict subintervals and their longer durations, Ecosystem 2 reaches the deadlock moment faster (t_{DE} = 149.47 s) comparing to Ecosystem 1 (t_{DE} = 219.17 s). The values for t_{DE} are provided with respect to the ET interval (t_{DE} column).

[1] Demand Data Repository 2 (DDR2) is an extensive ATM database, developed and maintained by EUROCONTROL. It contains a variety of traffic data, such as historical, filtered and forecast traffic datasets, as well the analytical tools and reporting sections. DDR2 is intended for use by the airspace users, the ATC as well as an academic research.

Table 2
Ecosystem 1 – trajectory segments

Flight ID	lat-1 (°)	long-1 (°)	alt-1 (ft)	time-1 (s)	lat-2 (°)	long-2 (°)	alt-2 (ft)	time-2 (s)
A/C1	50.498611	8.411389	25,000.00	60,629.00	49.932222	8.774444	32,000.00	60,927.00
A/C2	50.536087	8.527662	33,000.00	60,629.00	50.012420	8.791093	33,000.00	60,927.00
A/C3	50.119104	9.170007	36,000.00	60,629.00	50.273001	8.236522	36,000.00	60,927.00

Table 3
Ecosystem 2 – trajectory segments

Flight ID	lat-1 (°)	long-1 (°)	alt-1 (ft)	time-1 (s)	lat-2 (°)	long-2 (°)	alt-2 (ft)	time-2 (s)
A/C1	39.660556	–8.246667	25,000.00	66,994.00	40.107527	–8.318823	29,314.71	67,212.49
A/C2	40.401960	–7.906300	40,869.57	66,994.00	40.032700	–8.271550	30,314.71	67,212.49
A/C3	40.303130	–7.782880	37,000.00	66,994.00	40.022940	–8.265890	29,763.55	67,212.49
A/C4	39.515320	–8.196740	26,909.09	66,994.00	39.82233	–7.800140	30,000.00	67,212.49

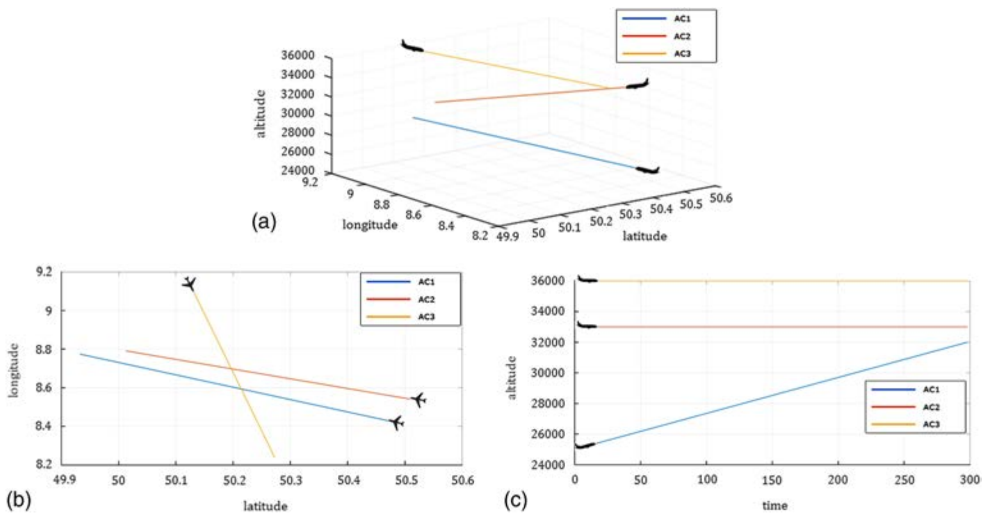

Figure 10. (Colour online) Ecosystem 1 in (a) 3D projection (latitude–longitude–time), (b) 2D planar projection (latitude–longitude) and (c) 2D vertical projection (time–altitude).

As the cumulative timestamps, those values correspond to 60,848.17 and 67,128.47 s for Ecosystems 1 and 2, respectively.

Figure 12(a) describes the resolutions capacity of Ecosystem 1 over its time, which equals to LAT, i.e., ET = LAT since $t_{CP} = 300$ s. In the case of Ecosystem 2 in Fig. 12(b), the capacity is measured within a time interval of 218 s (ET = 218). Obviously, in the latter case,

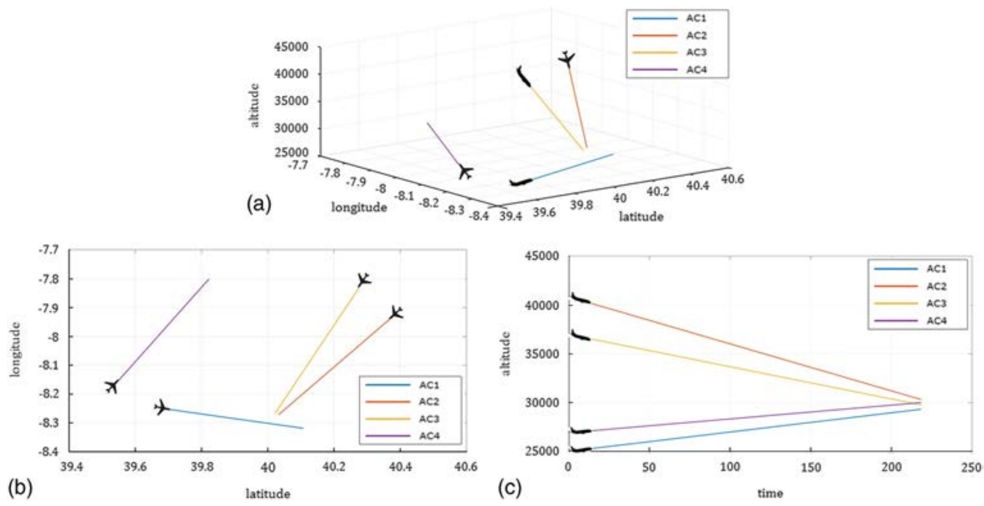

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Figure 11. (Colour online) Ecosystem 2 in (a) 3D projection (latitude–longitude–time), (b) 2D planar projection (latitude–longitude) and (c) 2D vertical projection (time–altitude).

Table 4
STI properties

Ecosystem ID	N_A	N_{STI}	I	S_{Amax}	t_{DE} (s)
Ecosystem 1	3	3	19	20,990	219.17
Ecosystem 2	4	4	33	50,291	149.47

the starting conflict point does not overlap with the closest point of approach (300 s after the ecosystem prediction moment) due to the operational factors, such as a relative geometry of the ecosystem trajectories and aircraft dynamics (position, velocity and flight mode). The solutions curve in the first case is decreasing at a lower rate with respect to the distribution (allocation) of the conflict subintervals produced by the aircraft interdependencies, with the distinction that, after 170 s, the reaming number of solutions drops at a higher rate. However, Ecosystem 1 still reaches deadlock after approximately 219 s, which is notably earlier from t_{CP} (80 s before). Regarding Ecosystem 2, the structure of the conflict subintervals is quite specific. The solutions curve is slightly maintained first 50 s, and then decreases at a quite low rate until 90 s. Because of the fact that frequency and duration of induced conflict subintervals is dominant after 100 s, the curve showed a drastically negative trend by a drastic drop in the capacity until the deadlock moment, that occurred approximately after 150 s. Based on the results presented in Table 4 and illustrated in Fig. 12, it can be concluded that both ecosystems faced a relatively shorter time in resolution with respect to the available times. The t_{DE} values for both ecosystems are significantly "shifted back" with respect to the t_{CP} values, as the complexities of evolving trajectories close to these instants are significantly increased. At those moments, no combination of the co-ordinated manoeuvers would remove the SSM infringement.

To co-operatively resolve the conflicts before collision avoidance, the aircraft are frequently required to align their velocities and adjust their inter-distances for computation of the

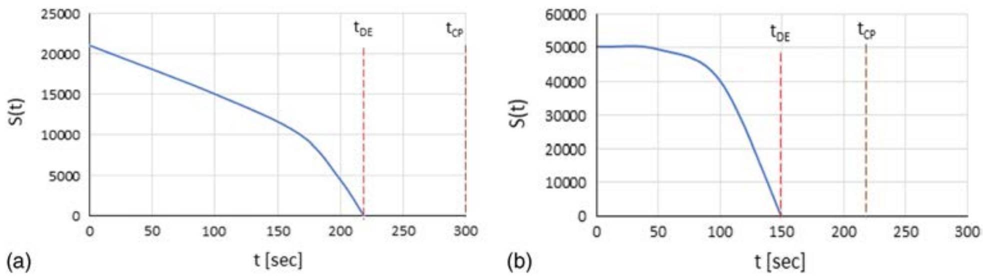

Figure 12. (Colour online) Decreasing rate in the number the resolutions of (a) Ecosystem 1 and (b) Ecosystem 2.

moment for triggering the co-operative resolutions. On the contrary, the ecosystem concept elaborated in this paper extends the time horizon providing more decision capacity at the SM level. The aircraft are aware of a potential EDE while flying to the CPA, and given a possibility to interactively negotiate the solutions, not requiring a priori any adjustment in velocity or heading and following the trajectories as approved. A time frame between the ecosystem prediction moment and a moment where ATC issues the compulsory directives is reserved for the ecosystem members to negotiate the system solutions. As indicated in the paper (Section 1), this negotiation might be implemented through the multi-agent ontology, in which each aircraft, as an intelligent agent, is enhanced by a self-governed capability to follow its own performance model, identify a preferred resolution, and try to impose it to other members. This framework provides the right support in the negotiation interactions, aiming to reach a timely resolutions consensus and avoiding the ATC directives before the EDE, which do not always consider the airspace users' preferences.

A decreasing rate between the available resolution capacity and elapsed time, expressing a potential path in negotiations among the aircraft, indicates that each missed moment in reaching an agreement among them reduces the number of remaining conflict-free solutions. Moreover, identification of a higher number of the causally involved aircraft into enlarged ecosystem volume provides an opportunity for an efficient modelling of the optimal trajectories, usually with the minimal deviations, and not compromising the separation criteria.

5.0 CONCLUSION AND FOLLOW-UP RESEARCH

This article relies on the previous research on the ecosystem creation algorithm, trying to identify the potential extra capacity in the search space of the conflict-free resolution manoeuvres. The main driver in this creation is the state-based CD in a pairwise aircraft encounter and its time instants, the prediction moment and starting conflict moment. The computational framework has presented the baseline in the identification of the STIs, expressing the structure of the conflict subintervals as a product of the potentially combined manoeuvres. The model has further included the analytical computation of decreasing rate in the amount of potential resolutions, as well as the ecosystem deadlock event in which this amount has reached the zero value. The study has shown a significance in providing the time capacity for a set of certain manoeuvres, at the operational level, when a severity of the conflict situation occurs very rapidly. A decreasing rate of the available ecosystem resources and an elapsed time described a potential path in a thorough analysis of resolution dynamics, meaning that each missed moment in making a resolution agreement induces less number of the conflict-free manoeuvres. The results, obtained through analysis of two simulated ecosystems, illustrated the cases of the variable resolution capacity that decreases over time at a different rate. With an increased ecosystem size and diverse trajectory geometries, the interdependencies structure becomes larger which produces less resolution capacity and a shorter ecosystem time. Finally, the ecosystem runs out of capacity at a certain time instant, which shows a time-critical nature of the ecosystem, where timely-advanced decision provides more flexible and resilient solution.

Further research is considered as multi-directional: analysis of multi-threat conflicts with respect to the time to CPA, and improving the computational performances. Moreover, an improvement in the ecosystem resolutions will focus on a multi-agent technology for simulation of the aircraft interactions during the negotiation intervals. That will provide more reliability in the solutions search space. Another task will be directed towards the generation of the resolution segments, based on the concept of performance-based operations. The main objective will be the computation of the tactical waypoints and definition of modelling elements that could provide smooth transition from the conflict-free amendments. The main criteria in the selection of the ecosystem solutions will be rather feasibility than optimality. Nevertheless, the early resolution agreements shall guarantee the smallest deviations from the RBT segments.

ACKNOWLEDGEMENTS

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5. Overall conclusions and future work

5.1 Conclusions

Present traffic alert and collision avoidance system, TCAS II, demonstrates high performance capabilities in the lower traffic density airspaces for one-on-one aircraft encounters, but unfortunately there are also some shortages due to induced collision in a proximate airspace that could emerge in certain surrounding traffic scenarios. Operational discontinuities and a lack of integration between planning the safety net layers may lead to incoherent resolution actions.

To address safety drawbacks in a multi-aircraft conflict environment, development of a robust conflict management framework is essential to support the functional integration of a collaborative and pro-active, socio-technical decision support tool, in which both the human interactions and automation (socio-technical system) play significant roles. Such a framework can be formalized through an adaptive, self-governed aerial ecosystem supported by a negotiation ontology, in which the ATM-relevant key performance indicators can be met. With the traffic increment in the future, flight efficient and safety ecosystem functions might facilitate the operational integration of trajectory and separation management with collision avoidance within different operational environments, such as direct routing or free routing.

This thesis contributes to the study for a better understanding of the means and effects of the spatiotemporal interdependencies among the aircraft pairs in a proximate airspace, as a consequence of the potential avoidance maneuvers that would precede the separation infringement. The proposed framework is represented through stepwise algorithms deploying the quantitative methods for analysis of the ecosystem resolution capacity over time, but also the deadlock instant. Those methods can be used for risk assessment and validation of the framework on the current and future traffic scenarios. The analytical studies provide a global perspective on complexity factors of the traffic scenario and a better insight on the time-criticality of the system in searching for a resilient and acceptable solution.

The main contributions to the aerial ecosystem state-of-the-art concept are pointed below:

- State space exploration of the conflict-free avoidance maneuvers for generation of the coherent system solutions in a short lookahead time. Complexity analysis based on the aircraft interdependencies is placed in function of the decision-making capacity in discrete moments.
- Quantification of the resolution capacity and determination of the potential deadlock for various conflict scenarios contributes to the understanding but also improvement of the system efficiency over stability up to certain scalability and time dependency threshold.
- Sensitivity in the ecosystem solution can be quantitatively analyzed through a ratio of configurable cluster and ecosystem parameters. A unit change in the parametric values could generate the ecosystem scenarios with different scalability and decision-making capacity.
- The methodology for the ecosystem identification, tracking and resolution opens a possibility for wide area applications, such as smart connectivity technologies for unmanned aerial vehicles. The integration of diverse vehicle types and anticipated scalability problems in near future is questioning the safety separation criteria, referring to a lack of the spatiotemporal requirements, especially in the phase of the mission planning.

The ecosystem methodology can be deployed as both the airborne and ground-based decision support tool. Currently developed for a higher en-route airspace, it is expected to be tested and implemented within terminal maneuvering area as well, where the negotiation ontology can be maximally utilized. Moreover, the expectation is directed to the future operational environments, such as performance-based operations.

5.2 Future work

Present work can be extended to the following research lines:

i. Uncertainty models for the resolution trajectories

Taking into account the deterministic methods, generation of the resolution trajectories (like other functions) is based on the computation of a fix-positioned CPA, and the complete cluster and ecosystem membership analysis together with the computation of resolution to the identified CPA. Although, it is not expected a huge uncertainty in the trajectory guidance within a LAT of 300 seconds, it must be considered uncertainties affecting the CPA computation to obtain a more robust evaluation of the decentralized resolution function. One of the potential solution will be description of the CPA as a time dependent small region inside the ecosystem, so the limits of the regions will be used for a robust resolution. The accuracy (i.e. tolerance) in size of this region could be measured and verified with the outputs coming from selected weather models and navigation and positioning error models.

ii. Ecosystem-level interdependencies

Considering a proximate ecosystem airspace, the natural question for consideration is an analysis of the interdependencies at an ecosystem level. In some traffic scenarios, one aircraft could be part of two nearby ecosystems, identified as surrounding traffic, and consequently the negotiation in one ecosystem can affect the geometry of the resolution trajectories in another one. Moreover, two or more nearby ecosystems might have interdependent resolutions. For instance, an aircraft from one ecosystem due to accumulated time delay in resolution might have an interdependency with an aircraft from another ecosystem, whose resolution trajectory might differ, or not, from its RBT. For all these situations, new and extended mitigation measures or metrics shall be introduced.

iii. Super or merging ecosystem

Different traffic characterics, i.e. flight configurations, aircraft dynamics and trajectory geometries, impose the frequent situations in which two or more ecosystems are detected very close to each other. Current aircraft clustering model does not provide the rigorous method for mitigation of such an effect, and in this case the ecosystems are merged in one super-ecosystem, that requires more complex analysis of the interdependencies. The new operational concepts, such as performance-based operatons in free route airspace could support this challenge.

iv. Time-based ecosystem

Time-based ecosystem is one the future research targets. A potential increment in a number of super-ecosystems opens a question of a spatial dimension of the ecosystem interdependencies, as any new maneuver at any moment might induce more complexity in the resolution. Thus, in some circumstances only a time property could successfully respond through the speed regulation. Depending on the airspace requirements and the user preferences, the phase speed combinations in different flight configurations (crussing – evolving) can adequately support to the time dimension of a conflict.

v. Functional integration with TCAS advisories

Although fully operable in the vertical plane, hybrid TCAS modifications have initially demonstrated good performances in the horzontal plane, applying also the short-term lateral offsets and vectoring by a heading change. This perspective seeks for a compatible integration with the ecosystem resolutions at the SM level in a way that any decided trajectory amendment within the ecosystem should be unambiguous for the TCAS logic on-board aircraft, non-necessarily triggering its advisory. The challenge in this integration may be subject to the next research level.

vi. Ecosystem resolution regions

The computation and segmentation of feasible regions inside the ecosystem volume has been an innovative initiative to analytically determine the bundles of the resolutions with a better computational efficiency, but there are several open issues that should be addressed: parametric adaptation to the fragmented, linear trajectory segments (i.e. ATS routes); refinement of the calculation method for the resolutions generation considering timely profiled solution segments and not only spatial; extend the resolution regions to the proximate volume segmentation (useful for the RPA applications); a potential introduction of combined delays with the speed adjustments.

vii. Aircraft performance models

The implemented framework has not considered a full spectrum of the aircraft performances, instead only a reference performance model has been defined. To tackle more realistic scenarios, the ecosystem framework should be enhanced with the performance of a mixture of medium and heavy aircraft category to evaluate if the decentralized multi-agent function is still robust, or is sensitive to this mixture, due to distinction in the airspace user's business model of the given aircraft types.

viii. Integration of a range of the cluster and ecosystem parametric values in the analytical expression for a deadlock event computation

Safety has been an indicator that cannot be compromised in any traffic scenario. The modeling 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 extend an analytical approach by qualitative (functional) identification of the appropriate avoidance manouvers (values for the heading or vertical rate increments/decrements) that must be preserved in any ecosystem before the starting moment of the initial pairwise conflict. Qualitative analysis of the deadlock event will then guarantee safety levels while computing the negotiation time limit without introducing latent capacity.

ix. Machine learning for surrounding traffic complexity

To enhance the acceptability of ecosystem framework starting the negotiation resolution mechanism 300 second before the CPA, it is important to obtain the maximum available information at the moment of the ecosystem creation in order to always maintain its evolution above safety criteria. The implementation of a machine learning algorithm to identify traffic patterns (i.e. the aircraft intents) and negotiation patterns would help to reach an earlier consensus and absorb any late moment uncertainty.

x. Cooperative and competitive multi-agent system for smart connectivity

Achieved results provide the baseline for implement a cooperative/competitive multi agent system framework for a decentralized control of the airspace capacity in urban areas. Further research to integrate the strategic decision-making when accepting transport missions and the operational decision-making when solving conflicts is under consideration as a promising mechanism to mitigate downstream conflicts due to local conflict resolutions.

Appendix A: Sensitivity analysis of conflict-free resolutions for the airborne cluster-ecosystem

Radanovic M., Piera M.A., Koca T. Sensitivity Analysis of Conflict-Free Resolutions for the Airborne Cluster-Ecosystem. Journal of Air Transportation, 2018, 26(1): 37-48. DOI: 10.2514/1.D0094.

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Sensitivity Analysis of Conflict-Free Resolutions for the Airborne Cluster–Ecosystem

Marko Radanovic,* Miquel Angel Piera Eroles,† and Thimjo Koca‡
Autonomous University of Barcelona, Sabadell, Spain

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To support the future automation of air traffic management, this study examines a decrement in the number of feasible, conflict-free avoidance maneuvers within a tactical air traffic system, relying on the concept of an airborne ecosystem. An ecosystem represents a set of aircraft with the trajectory-amendment, decision-making capability, whose trajectories are identified inside a computed airspace volume and causally involved in a safety event that is predicted for a certain look-ahead time from their current positions. The concept is based on the predicted conflict between two aircraft, whose trajectory segments are used for detection of the surrounding aircraft by identification of the spatiotemporal interdependencies. The potential resolution capacity is characterized by a decreasing rate of the feasible solutions over time, while the aircraft are flying toward the closest point of approach. Causal analysis was performed via the initialization of different cluster–ecosystem transitions with the goal of measuring the scenarios complexity in terms of the time-based conflict-free solutions, in front of the elapsed time to the aircraft collision. Simulation of eight ecosystems generated from two pairwise conflicts with different avoidance capacities illustrates a potential of negotiation as the aircraft tendency to reach a resolution agreement via early or late decisions.

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Nomenclature

C_A	=	total number of conflict amendments
CPA	=	closest point of approach
DA	=	deflection angle, deg
EIP	=	ecosystem identification point
FPA	=	flight-path angle, deg
H_{CB}	=	horizontal cluster buffer, n mile
h_{CPA}	=	altitude coordinate at the closest point of approach, ft
h_{EIP}	=	altitude coordinate at the ecosystem identification point, ft
h_L	=	computed lower altitude, ft
h_{min}	=	minimum considered altitude coordinate, ft
h_{max}	=	maximum considered altitude coordinate, ft
h_U	=	computed upper altitude, ft
I	=	total number of conflict intervals
K	=	conflict interval index
LAT	=	look-ahead time, s
M	=	number of maneuvers
N_A	=	number of ecosystem aircraft
N_{STI}	=	number of spatiotemporal interdependencies
p	=	checking/sampling time rate, s
S_A	=	total number of conflict-free amendments
SSM_H	=	standard separation minima in the horizontal plane, n mile
SSM_V	=	standard separation minima in the vertical plane, ft
ST	=	surrounding traffic
STI	=	spatiotemporal interdependencies
TM_A	=	theoretical number of ecosystem maneuvers
TWP	=	tactical waypoint
t	=	random time instant within look-ahead time, s
t_{CPA}	=	time instant at the closest point of approach, s
t_E	=	ending moment of conflict interval, s
t_{IN}	=	time instant for ecosystem triggering, s
t_{RA}	=	resolution advisory time instant, s
t_S	=	starting moment of conflict interval, s
t_{TA}	=	traffic advisory time instant, s
V_{CB}	=	vertical cluster buffer, ft
VR	=	vertical rate, ft/min
η	=	exponential decay constant
λ_{CPA}	=	longitude coordinate at the closest point of approach, °
λ_{EIP}	=	longitude coordinate at the ecosystem identification point, °
λ_L	=	computed lower longitude, °
λ_{min}	=	minimum considered longitude coordinate, °
λ_{max}	=	maximum considered longitude coordinate, °
λ_U	=	computed upper longitude, °
φ_{CPA}	=	latitude coordinate at the closest point of approach, °
φ_{EIP}	=	latitude coordinate at the ecosystem identification point, °
φ_{min}	=	minimum considered latitude coordinate, °
φ_{max}	=	maximum considered latitude coordinate, °
φ_L	=	computed lower latitude, °
φ_U	=	computed upper latitude, °

I. Introduction

THE continuous increase in air traffic demand could lead to some situations in which the separation minima infringements in diverse highly dense sectors could occur. Such situations generate intensive pressure on the en route operations at the tactical level. Consequently, there is a demand for more efforts in the improvement of air traffic control (ATC) technology to satisfy the main air traffic management (ATM) criteria, in terms of increase in capacity, cost-efficiency, and safety [1,2]. The SESAR and NextGen joint initiatives [3,4] called for a complete replacement of the centralized tactical ATC interventions with a more efficient decentralized separation-management (SM) operation relying on the advanced decision-support tools (DSTs). This requires important changes in the situational awareness, functionalities of tools, and responsibilities of the ATM system [5].

The traffic alert and collision avoidance system (TCAS), as an airborne autonomous system, demonstrates excellent performance for pairwise and multithreat aircraft encounters but, unfortunately, suffers from a lack of performance logic owing to well-reported induced collisions from the surrounding traffic (ST) scenarios [6]. Moreover, TCAS resolution advisories (RAs) are frequently inconsistent with the standard ATC procedures [7] and create a lack of integration between the SM, at the tactical level, and the collision

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*Ph.D. Researcher, School of Engineering, Department of Telecommunications and Systems Engineering.
†Full Professor, School of Engineering, Department of Telecommunications and Systems Engineering.
‡Ph.D. Researcher, School of Engineering, Department of Telecommunications and Systems Engineering.

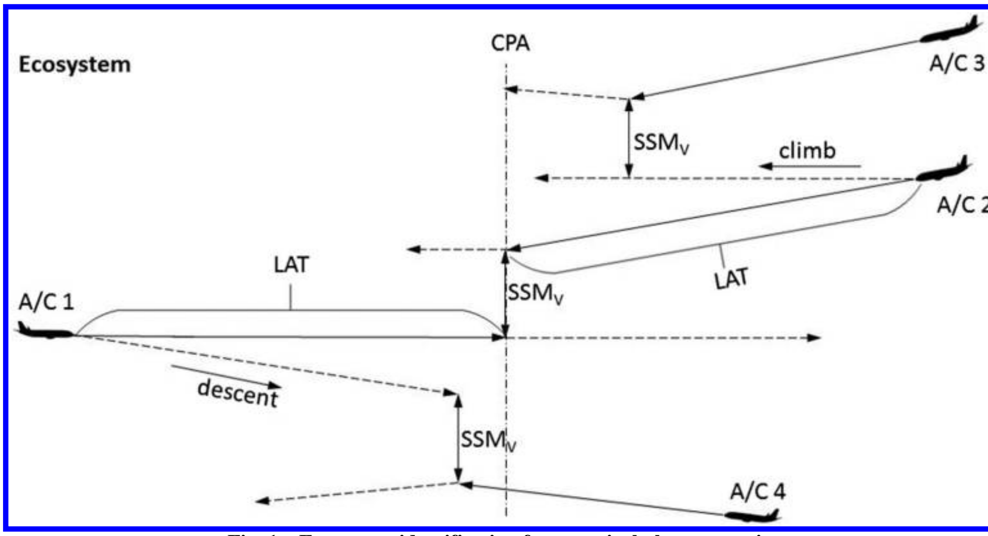

Fig. 1 Ecosystem identification for a vertical plane scenario.

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avoidance (CA), at the operational level. Therefore, new research directions are required toward the development of a collaborative and decentralized SM layer, on which both human behavior and automation will be fully aligned. This envisages the operational integration of the safety procedures in such a way that any pair of aircraft involved in a conflict, together with the ST aircraft, behaves as a stable conflict-free air traffic system. Furthermore, the integration should be characterized by a set of critical information on the feasible resolution trajectories, proposed via the development of both airborne and ground-based DSTs.

This study follows a current research on the concept of an airborne ecosystem, a tactical air traffic system [8], particularly focusing on the development of the stepwise ecosystem identification algorithm. An ecosystem, as a multi-agent system [9], presents a set of aircraft with the trajectory-amendment and decision-making capability, whose trajectories are identified inside a computed airspace volume (cluster) and are causally involved in a safety event. The concept is based on a predicted conflict between two aircraft, whose trajectory segments are used for the detection of the ST aircraft using the identification of the spatiotemporal interdependencies (STIs). The STIs are determined by the combinations of the potential avoidance maneuvers between the conflicting aircraft and durations of the conflict intervals. The determination process is subsequently further extended to each pair of aircraft involved in a detected conflict. Consequently, the ecosystem aircraft aim for the formation of a cost-efficient SM net that allows cooperative actions (interactions) in the generation of resolution trajectories. The principal objective is the enhancement of aircraft communications to safely exploit the existing airspace capacity.

The system is triggered by an en route traffic controller in the moment of a predicted conflict between the reference business trajectories (RBTs) of two aircraft [10]. This prediction is determined by the search function for the given look-ahead time (LAT) between the ecosystem identification point on the RBT and closest point of approach (CPA), taking into consideration the dynamic states of both aircraft. Once detected, two aircraft are searching for the conflict avoidances in a four-dimensional (4-D) space using a given set of maneuvering parameters and starting from the identification points. If any of the avoidance maneuvers produces a conflict with an ST aircraft flying in a nearby airspace, this neighboring aircraft becomes an ecosystem member and further participates in the negotiation for trajectory resolution. This induced conflict is characterized by the STIs, which express a spatial (three-dimensional) loss of the standard separation minima (SSM) between the determined positions of the aircraft in initial conflict along its amending trajectory and an ST aircraft along its RBT. The SSM is componentized into two projections: the horizontal minima of 5 n mile and the vertical minima of 1000 ft (i.e., $SSM_H = 5$ n mile and $SSM_V = 1000$ ft). The basic ecosystem concept in the vertical plane with two ST aircraft, A/C3 and A/C4, is illustrated in Fig. 1. The conflict between A/C1 and A/C2 is predicted within the LAT. A/C4 is identified as an ecosystem member by a potential descending maneuver of A/C1, whereas a potential climb maneuver of A/C2 identifies A/C3 as an ecosystem member.

A resolution trajectory within an ecosystem can be computed as a two-leg trajectory: amending and resuming leg. Both legs are characterized by linearity and constant velocity. A tactical waypoint (TWP) is a 4-D point that links the two aforementioned legs. The TWPs must be conflict-free, i.e., at the given time instant t, the SSM in both the horizontal ($SSM_H = 5$ n mile) and vertical planes ($SSM_V = 1000$ ft) between its position and the position of any point along the ST trajectory must be satisfied. The resolution trajectory also comprises the second TWP, which belongs to the RBT. The resuming leg ends at this point (Fig. 2). Depending on the aircraft states and flight modes (the closure rates) and the geometries of the surrounding trajectories, a resolution trajectory can be symmetric and asymmetric in terms of the segment length.

From the perspective of airspace users, the deviation from the RBT should be minimal, while also requiring a nondemanding maneuver. However, this deviation highly depends on the optimal and feasible combinations of all the ecosystem resolutions.

The concept is based on the so-called explicit coordination in the conflict resolution. In many cases, the explicit coordination is an approach that is generally avoided for the main reason of the time it might take to solve a cluster of conflicts. Waiting for a new resolution means it could become more extreme than might have been necessary. Nevertheless, the available solution space is compressed over time.

A vector-based approach with implicit coordination has also been shown to be able to solve multi-aircraft conflicts in an effective and efficient way without the risks of deadlocks and waiting times. For instance, the modified voltage potential (MVP) [11] is one of the approaches that has been implemented for the conflict resolution in the multi-aircraft environment. Within this approach, the conflict detection is performed by a state-based extrapolation of traffic positions, within a prescribed LAT, using traffic transmitted state information (position, speed, and heading). MVP is subsequently used to resolve conflicts in a pairwise manner. This method results in the implicit cooperative resolution strategies, where the distance between the conflicting aircraft at the CPA is increased to, at least, the minimum separation requirements. However, the concept extends the TCAS logic as LAT is this case is set to 60 s before the CPA, which practically means the method does not consider the SM-CA integration. Furthermore, less available space for the cooperative resolution exists, and consequently the business preferences of the airspace users cannot be fully considered.

Another factor delimiting this approach in the effect of swarming [12]. To cooperatively resolve the conflicts before collision avoidance,

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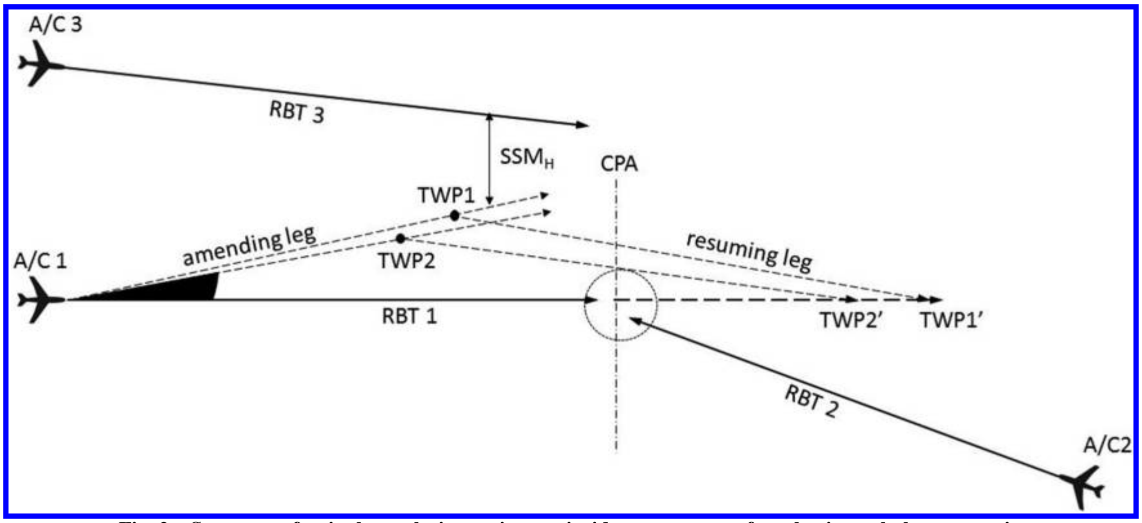

Fig. 2 Structure of a single resolution trajectory inside an ecosystem for a horizontal plane scenario.

the aircraft are required to align their velocities and adjust their interdistances for computation of the moment for triggering the cooperative resolutions. On the contrary, the ecosystem concept extends the time horizon providing more decision capacity at the SM level. The aircraft are aware of a potential deadlock moment while flying to the CPA, and given a possibility to interactively negotiate the solution, not requiring a priori any adjustment in velocity or heading and following the trajectories as approved. Moreover, identification of a higher number of the causally involved aircraft into an enlarged ecosystem volume provides an opportunity for an efficient modeling of the optimal resolution trajectories, usually with the minimal deviations.

This paper elaborates the rate of reduction in the number of conflict-free avoidance maneuvers (S_A) over the ecosystem time. This computation is directly obtained as a difference between the theoretical ecosystem maneuverability (TM_A) and the total number of conflict-avoidance maneuvers (C_A). C_A is derived from the identification of STIs among the aircraft. The rate is expressed by a continuous loss of solutions for which the maximum number of conflict-free amendments, available from the moment of triggering of the ecosystem, decreases over the LAT [13]. C_A is obtained with respect to the computed cluster–ecosystem parameters derived from the dynamic characteristics of 4-D flight plans used for the algorithm development and testing. This paper further examines the ecosystem complexity ratio between available resources and elapsed time by introducing the modifications in the cluster–ecosystem parameters and, consequently, changes in the STI structure.

In addition to this introductory section, this paper comprises five other sections. Section II is dedicated to the time horizon problem and incoherency in the safety net transition. Section III analyzes the combinations of cluster–ecosystem transitions and describes STIs among the aircraft, and Sec. IV provides the computation of the number of conflict amendments and total system resolutions. Section V discusses the simulation results, and the concluding remarks and directions for the follow-up research are given in Sec. VI.

II. Problem Definition

This section illustrates two key TCAS problems. This justification requires new quantitative resolution methods to enhance the present safety nets and tackle conflicts in complex scenarios.

A. Time Horizon Problem

To illustrate the concept of operational emergent dynamics [14] leading to an induced collision, it is considered an initial state of a nonvectored traffic scenario [15,16]. Figure 3 illustrates a scenario with four aircraft (A/C01, A/C02, A/C03, and A/C04) flying over

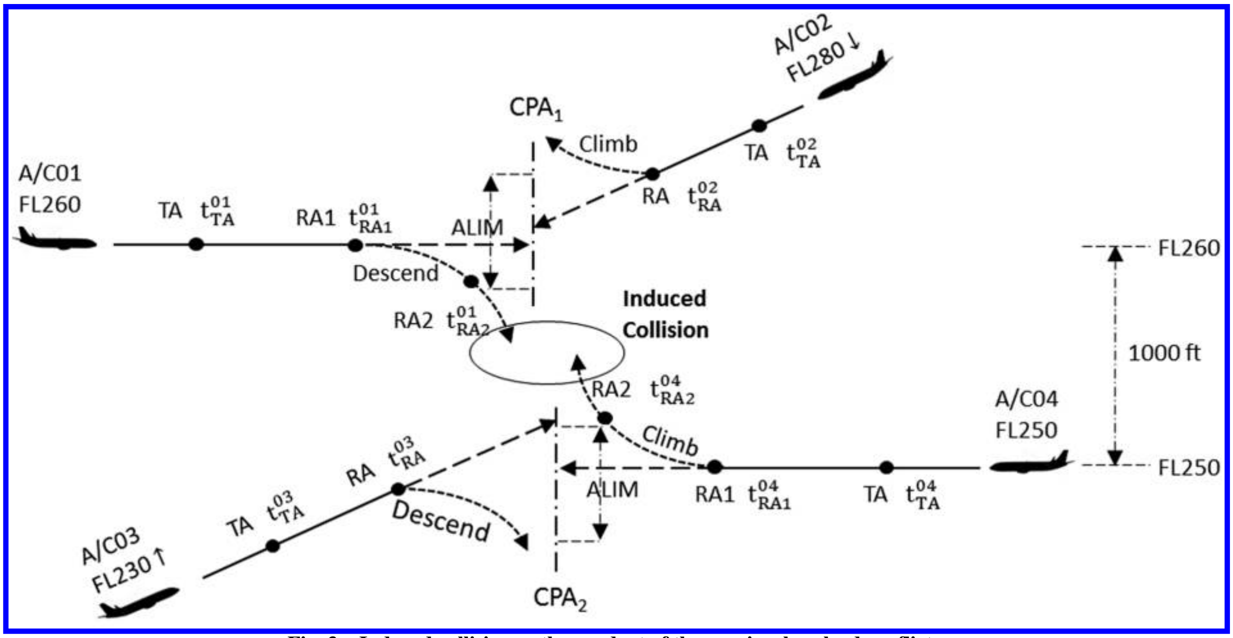

Fig. 3 Induced collision as the product of the previously solved conflicts.

trajectories that form two predicted encounters (A/C01–A/C02 and A/C03–A/C04).

A/C01 is cruising on FL260 while A/C02 starts descending at FL280 in the opposite direction from A/C01, which assumes a direct approach to A/C01 with a loss of height. On the other side, A/C03 starts climbing at FL230, and, with its increase in height, approaching to A/C04, which is cruising at FL250 in the opposite direction from A/C01. As it can be seen, both conflicts are successfully resolved after activation of TAs, at the time stamps of four aircraft t^{01}_{TA}, t^{02}_{TA}, t^{03}_{TA}, and t^{04}_{TA}, respectively, and then followed by the corresponding RAs, at the time stamps t^{01}_{RA1}, t^{02}_{RA}, t^{03}_{RA}, and t^{04}_{RA1}. The required minimal vertical distance, ALIM, has been successfully achieved at both CPAs.

As within the altitude range FL200–FL420, TCAS traffic advisories (TAs) are triggered 60 s before and RAs 35 s before the CPA [17,18] once resolved conflicts produce very high uncertainty in guidance over amended RBTs. After their amendments, A/C01 and A/C04 generate a new conflict, denoted as an induced conflict. It presents a product of downstream flow effect and is characterized by an instantaneous RA alert, while the aircraft is still performing the requested resolution maneuver, and not resumed to its RBT [19]. In this case, both aircraft are automatically alerted by the succeeding RAs, at time stamps t^{01}_{RA2} and t^{04}_{RA2}, respectively. Unfortunately, because of insufficient time for the appropriate succeeding maneuvers, two aircraft came into induced collision.

Introducing more conservative limits about the amount of aircraft coexisting in an airspace volume would be a natural mechanism to mitigate emergent dynamics caused by the ST effects [20,21]. However, the latent capacity and low efficiency indicators discourage this approach. Instead, a deep understanding of the ST behavior paves the way for an efficient ATM automation system. The use of formal methods in the ST analysis enhances the implementation of conflict resolution tools that could guarantee deadlock-out scenarios [22]. Considering again the example illustrated in Fig. 3, it is highlighted the importance to identify for each encounter geometry the time limit at which the RA should be fired, to avoid an induced collision or unacceptable safety levels.

On the other side, the current safety management systems have neither the functionalities nor the capabilities to comprehensively analyze the ST effects across the full airspace, to identify potential induced collisions. The common practice implemented by the air traffic controllers is identification of the safety event using the time thresholds and a separation provision by assigning the standard, but instantaneous, horizontal and vertical maneuvers. For instance, the state-based properties in a conflict resolution, such as the heading and speed vectors, are provided instantaneously, in a procedural way, but without any supporting tool to analyze the ST dynamics with the trajectory geometries [23].

B. Incoherence Between Safety Net Layers

Increased traffic demand and trajectory deviations owing to environmental uncertainties enlarge the scope of the ATC workload at tactical levels [24]. This level is timely framed between two safety thresholds: midterm conflict detection, which is activated approximately 15 min before the CPA, and short-term conflict alert (STCA), which is triggered between 120 and 90 s before the CPA. ATC provides the separation services by directing one or more aircraft off their trajectories. After STCA, the two aircraft in conflict potentially enter a CA layer characterized by a non-ATC separation provision, but the autonomous airborne advisories generated by the TCAS logic [25].

Potential incoherence between SM and CA could occur owing to differences between the ATC directive after STCA and the TCAS advisory. In many cases, the ATC system fails to apply a separation standard after the STCA threshold, which activates TCAS TA. Because the perception of TCAS is based on a set of logic advisories and considers only nearby airspace volumes, the advisory is frequently opposite of an ATC directive, which is based on a larger, sector-based volume. This situation may create ambiguity in the decision process of the pilot in command and provoke a higher severity of the conflict event [26]. Moreover, TCAS advisories sometimes require more demanding maneuvers by pilots from the aspect of flight efficiency [27].

The proposed ecosystem concept relying on multi-agent technology intends to solve the time horizon paradigm via the identification of STIs as a product of potential maneuvers among the ecosystem aircraft. The core of the concept lies in a decentralized decision-making process. Based on the business rules of the airspace users, the aircraft forming the ecosystem act as the intelligent agents to cooperatively negotiate their most optimal preferences in case of the RBT amendments, for a satisfactory system solution. In this way, the ecosystem demonstrates a separation capability as a shift from a centralized ATC system to an airborne decentralized, decision-making system at both tactical and operational level [28]. The ST can be identified in advance by applying the proper operational metrics at specific time instances preceding the conflict. Figure 4 illustrates the ecosystem positioning within the operational time horizon. This position should guarantee coherence between the SM and CA layers and the functionalities before and after the STCA threshold. However, in the multi-aircraft environment, the timing problem of the collision avoidance in a full operational context must account for the aircraft communications and the task execution delays, as well as the timing in the selected maneuvers [29], which overall requires more intent data for the solutions generation. Therefore, this study does not cover the complete timing problem at the operational level.

III. Spatiotemporal Interdependency Identification from the Cluster–Ecosystem Transition

A. Concept of the Cluster–Ecosystem Transition

The ecosystem model has been developed via a stepwise algorithm consisting of three functions: state-based conflict detection [22], cluster creation, and ecosystem identification. The cluster creation function is to quantify the number of surrounding trajectories around a detected conflict [30,31]. A cluster is created considering a sequence of filters. For a given conflict, a 4-D CPA of both aircraft (i.e., CPA_1 and CPA_2) is taken as an input. Given that, from t_{CPA1} and

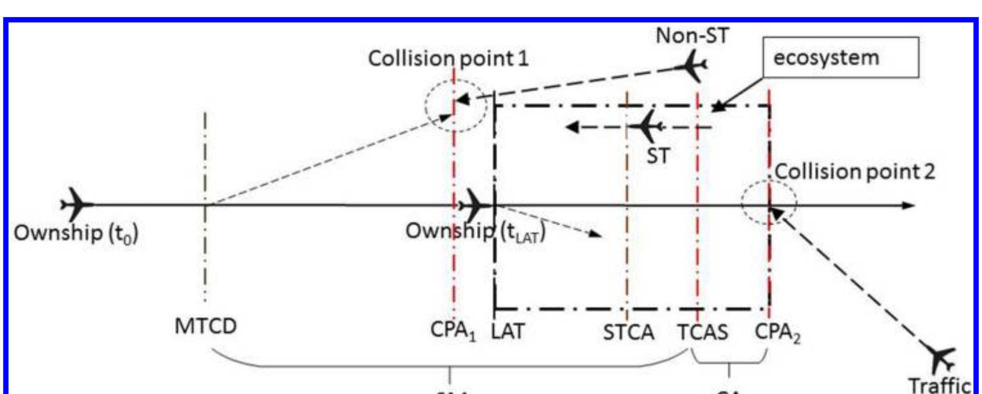

Fig. 4 Ecosystem positioning as a response to the safety-layer incoherence.

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t_{CPA2}, the new positions of both aircraft are predicted using the constant interval of 300 s as LAT. In other words, the LAT is propagated from the CPA back for a definition of an ecosystem identification timestamp t_{EIP}. The three-dimensional positions at the ecosystem identification points (EIPs) are then identified for both aircraft in conflict, and the cluster volume is built by adding/subtracting the safety buffers to/from the maximal/minimal values of the EIP coordinates. $\varphi_{\min}$ is the minimal latitude identified in the interval $[t_{\mathrm{EIP}}, t_{\mathrm{CPA}}]$, $\lambda_{\min}$ is the minimal longitude, and $h_{\min}$ is the minimal altitude. Maximum values, namely $\varphi_{\max}$, $\lambda_{\max}$, and $h_{\max}$, are defined analogously. The ST members are analyzed in the ecosystem framework as aircraft whose RBTs during the interval $[t_{\mathrm{EIP}}, t_{\mathrm{CPA}}]$ are identified through the 4-D points, such that their latitudes, longitudes, and altitudes are inside the cluster volume. The cluster creation is therefore performed through seven steps.

1) Feeding the cluster creation function with the output data from the conflict detection procedure, namely $\mathrm{CPA}_1[\varphi_{\mathrm{CPA1}}, \lambda_{\mathrm{CPA1}}, h_{\mathrm{CPA1}}, t_{\mathrm{CPA1}}]$ and $\mathrm{CPA}_2[\varphi_{\mathrm{CPA2}}, \lambda_{\mathrm{CPA2}}, h_{\mathrm{CPA2}}, t_{\mathrm{CPA2}}]$.

2) Time-based projection of LAT in a reverse way (i.e., $t_{\mathrm{EIP}} = t_{\mathrm{CPA}} - \mathrm{LAT}$).

3) Matching the corresponding coordinates at the ecosystem prediction instant for both trajectories, φ_{EIP1}, λ_{EIP1}, h_{EIP1}, φ_{EIP2}, λ_{EIP2}, h_{EIP2}.

4) Finding the minimal and maximal values of the spatial coordinates from steps 1 and 3:

$$\begin{aligned}
\|\varphi_{\min}\| &= \min(\varphi_{\mathrm{CPA1}}, \varphi_{\mathrm{CPA2}}, \varphi_{\mathrm{EIP1}}, \varphi_{\mathrm{EIP2}})\\
\|\varphi_{\max}\| &= \max(\varphi_{\mathrm{CPA1}}, \varphi_{\mathrm{CPA2}}, \varphi_{\mathrm{EIP1}}, \varphi_{\mathrm{EIP2}})\\
\|\lambda_{\min}\| &= \min(\lambda_{\mathrm{CPA1}}, \lambda_{\mathrm{CPA2}}, \lambda_{\mathrm{EIP1}}, \lambda_{\mathrm{EIP2}})\\
\|\lambda_{\max}\| &= \max(\lambda_{\mathrm{CPA1}}, \lambda_{\mathrm{CPA2}}, \lambda_{\mathrm{EIP1}}, \lambda_{\mathrm{EIP2}})\\
\|h_{\min}\| &= \min(h_{\mathrm{CPA1}}, h_{\mathrm{CPA2}}, h_{\mathrm{EIP1}}, h_{\mathrm{EIP2}})\\
\|h_{\max}\| &= \max(h_{\mathrm{CPA1}}, h_{\mathrm{CPA2}}, h_{\mathrm{EIP1}}, h_{\mathrm{EIP2}})
\end{aligned} \tag{1}$$

5) Addition/subtraction of safety buffers to/from the values in step 4 to obtain the new vertices of a box-shaped cluster (index "L" denotes the lower level and "U" the upper one for each of the coordinates):

$$\begin{aligned}
\varphi_L &= \varphi_{\min} - H_{\mathrm{CB}}\\
\varphi_U &= \varphi_{\max} + H_{\mathrm{CB}}\\
\lambda_L &= \lambda_{\min} - H_{\mathrm{CB}}\\
\lambda_U &= \lambda_{\max} + H_{\mathrm{CB}}\\
h_L &= h_{\min} - V_{\mathrm{CB}}\\
h_U &= h_{\max} + V_{\mathrm{CB}}
\end{aligned} \tag{2}$$

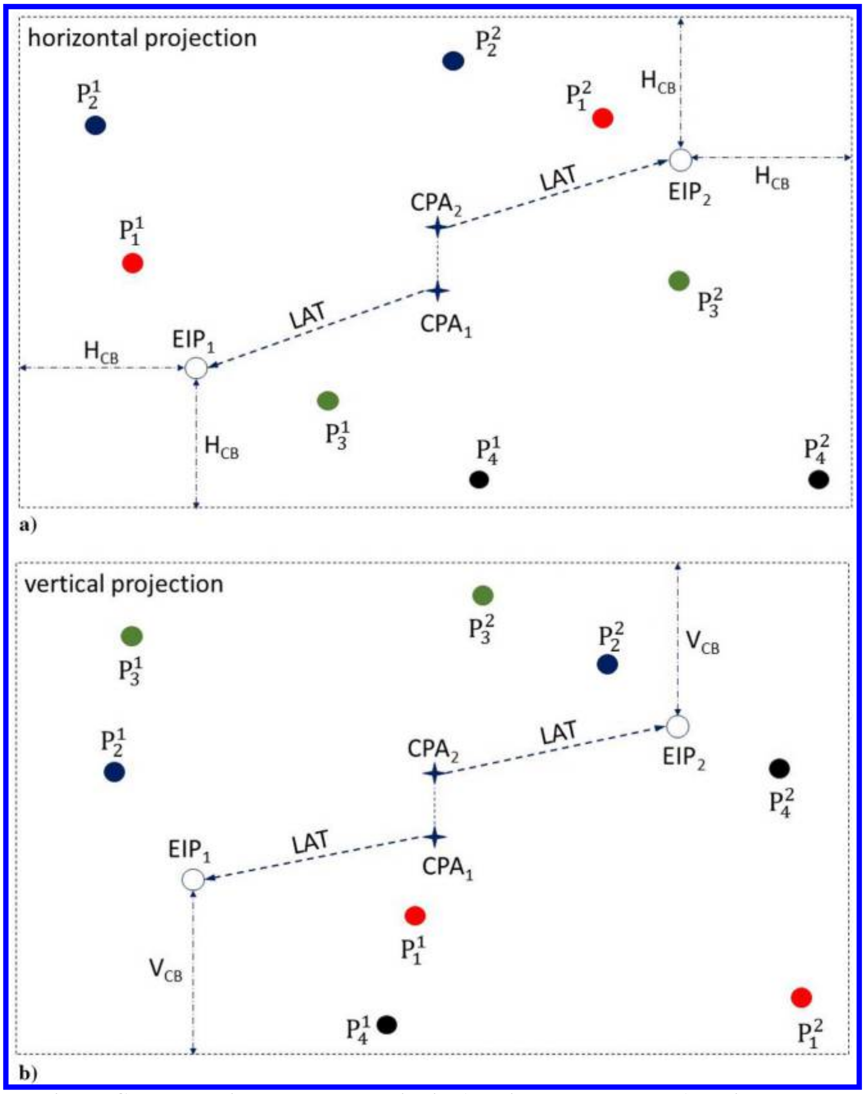

Fig. 5 Cluster creation procedure applied in a) horizontal plane, and b) vertical plane.

6) Filtering of the extracted traffic sample between the following ranges: a) $\varphi_L - \varphi_U$ (latitude column), b) $\lambda_L - \lambda_U$ (longitude column), and c) $h_L - h_U$ (altitude column).

7) Identification of all 4-D points inside the cluster volume and matching them with the corresponding flight identifiers to report the cluster members.

Figure 5 describes the cluster creation procedure projected in the horizontal and the vertical plane. The shortest distance is detected between the points CPA_1 and CPA_2. The points around conflict aircraft match the surrounding trajectories.

EIP_1 and EIP_2 present the ecosystem identification points of the conflicting aircraft pair, A/C1 and A/C2, respectively. There are four ST trajectories, each identified by two 4-D points (colored dots). Hence, P_1^1, P_2^1, P_3^1, and P_4^1 denote the first 4-D points, and P_1^2, P_2^2, P_3^2, and P_4^2 denote the second 4-D points of ST1, ST2, ST3, and ST4, respectively. Figure 6 illustrates an ecosystem scenario with a predicted conflict between aircraft A/C1 and A/C2 and three identified ST aircraft, namely ST1, ST2, and ST3. A/C1 and A/C2 are positioned at their triggered 4-D points from which the cluster volume has been computed, consistent with the adopted spatial distances/buffers. The horizontal cluster buffer (H_{CB}) is set to 15 n mile (Fig. 6a), and the vertical buffer (V_{CB}) is set to 3000 ft (Fig. 6b). Taking into analysis the closure rates between the pairs of aircraft, the given metrics have been selected with respect to the following two derivations.

1) In any encounter and undertaking geometry formed by two conflicting aircraft, the metrics dimension a proper airspace volume for the conflict-free avoidance maneuvers and system solution.

2) For any encounter and undertaking geometry formed by one conflicting and one or more ST aircraft, the metrics provide a sufficient spatiotemporal capacity for a safe maneuverability.

Within a box-shaped volume, any waypoint belonging to an ST trajectory identifies not only the cluster member but also a potential ecosystem member. Furthermore, the cluster trajectories projected very close to the cluster bounds may be limited in maneuverability in case any aircraft is operating out of the cluster volume but is noncompliant with the SSM criteria. This fact may affect the aircraft in searching for all potential resolutions. Therefore, before applying the ecosystem identification, it is necessary to test the extended cluster volume. The extension measures correspond to SSM_H (Fig. 6a) and SSM_V (Fig. 6b).

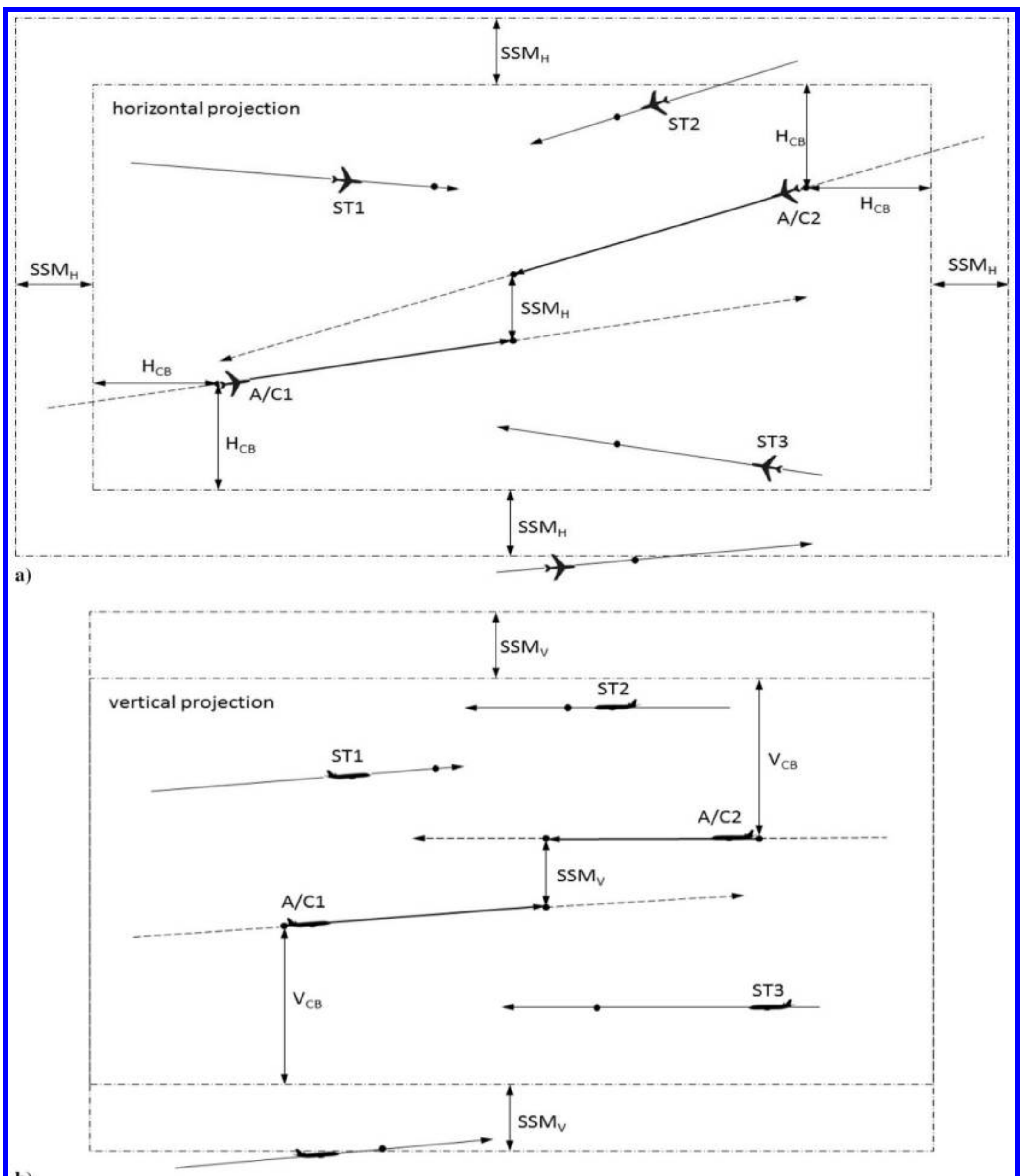

Fig. 6 Projection of a standard and modified cluster in a) horizontal plane, and b) vertical plane.

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The ecosystem algorithm determines all the cluster members as the ST aircraft for which the loss of SSM with any of two conflicting aircraft would occur if this aircraft performed a given avoidance maneuver at any moment during LAT. However, the membership identification is performed only once, in the moment of the ecosystem initialization (300 s before the CPA). Therefore, once computed, membership size (a set of the ecosystem aircraft) is given as a static property and not dynamically updated during the resolution phase. Notably, ecosystem identification is a spatiotemporal category as an applied maneuver generates the conflict interval(s) with the neighboring aircraft. Maneuverability is applied in both the horizontal and vertical planes using the first set of parametric values: 1) m_1: left heading change with the deflection angle (DA) of $+30$ deg; 2) m_2: right heading change with the DA of -30 deg; 3) m_3: climb at the vertical rate (VR) of $+1000$ ft/min and the flight-path angle (FPA) of $+2$ deg; and 4) m_4: descent at the VR of -1000 ft/min and FPA of -2 deg.

The paper further explores the size of the ecosystem membership and STIs by applying the second set of aircraft performance parameters: 1) m_1', with the DA of $+45$ deg; 2) m_2', with the DA of -45 deg; 3) m_3', at the VR of $+1500$ ft/min and FPA of $+3$ deg; and 4) m_4', at the VR of -1500 ft/min and FPA of -3 deg.

Uncertainties in the performance parameters, such as a time change in vectoring the certain avoidance maneuvers, are not considered. The aircraft as a complex inertial system takes a certain amount of time in achieving the requested maneuver, which raises the question about dynamicity of the ecosystem scenario and its membership configuration. However, for the sake of simplicity, the avoidance maneuvers are here assumed instantaneously effective. The objective is to identify the complexity levels of different ecosystems because the spatiotemporal interdependencies might differ from the ones identified by the first set of parametric values. Furthermore, potentially more demanding maneuvers in the case of the second set of values could possibly generate more interdependencies and, consequently, provide fewer amendment solutions. However, the second set of values might result in an increased number of resuming solutions for each computed TWP, providing more latent capacity for delayed resolution trajectories. Figure 7a illustrates the case of a left heading change, whereas Fig. 7b illustrates a climbing amendment.

B. Spatiotemporal Interdependency Identification

The algorithm computes the time windows for each ecosystem aircraft in which any potential cooperative or noncooperative maneuver could produce loss of SSM, both laterally and vertically. These windows are subintervals of LAT, and the number of conflict maneuvers within each window is obtained as per the defined time check rate (by default, 1 s) along the RBT. Figure 8 shows an example of the conflict intervals generated using a left heading change.

When A/C1 performs this maneuver at a triggered 4-D point using both DA values, $+30$ and $+45$ deg, it generates two conflict intervals with an ST aircraft (A/C3) that are of different duration. For $+45$ deg change, the conflict interval 1, determined by the avoidance maneuvers m_1', presents a subinterval of the conflict interval 2 generated by the m_1-avoidance maneuvers using the $+30$ deg heading change. This situation explains the fact that two aircraft, with the current flight configurations and trajectory geometries relative to each other, would maintain a longer conflict time for a lower heading change value. However, if any of the aspects in the scenario changed, it would affect the duration of the conflict interval.

The number of STIs (N_{STI}) among the pairs of aircraft is obtained using four types of avoidance maneuvers, m_1, m_2, m_3, and m_4, as well as an additional one, m_0: the RBT follow-up. In this study, therefore, five types of maneuvers are considered (i.e., $M = 5$). Each interdependency contains one or more conflict intervals, and the total number of conflict intervals (I) satisfies the following condition:

$$I \le \frac{N_A(N_A - 1)}{2} M^2 \tag{3}$$

where N_A denotes the number of aircraft. M^2 is a derived property indicating the total number of maneuvering combinations applied to a pair of aircraft. In general, it refers to the aircraft in initial conflict. An example of the three interdependencies ST_1, ST_2, and ST_3 among

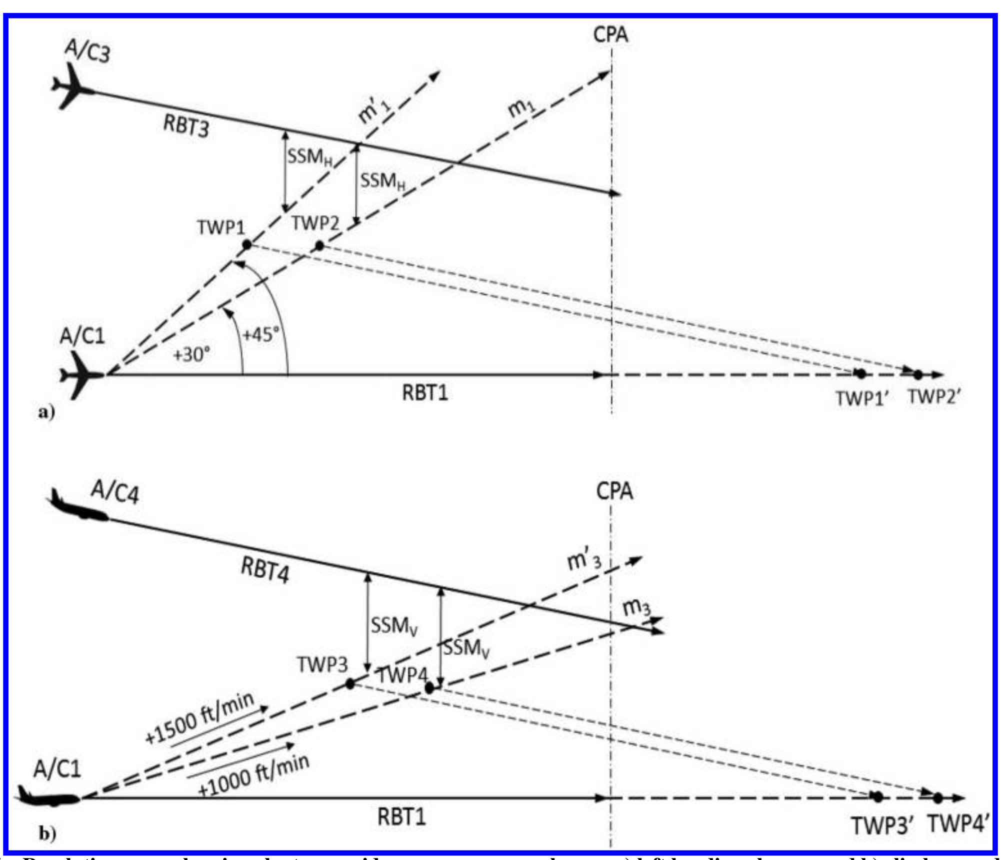

Fig. 7 Resolution examples given by two avoidance maneuvers values as a) left heading change, and b) climb amendment.

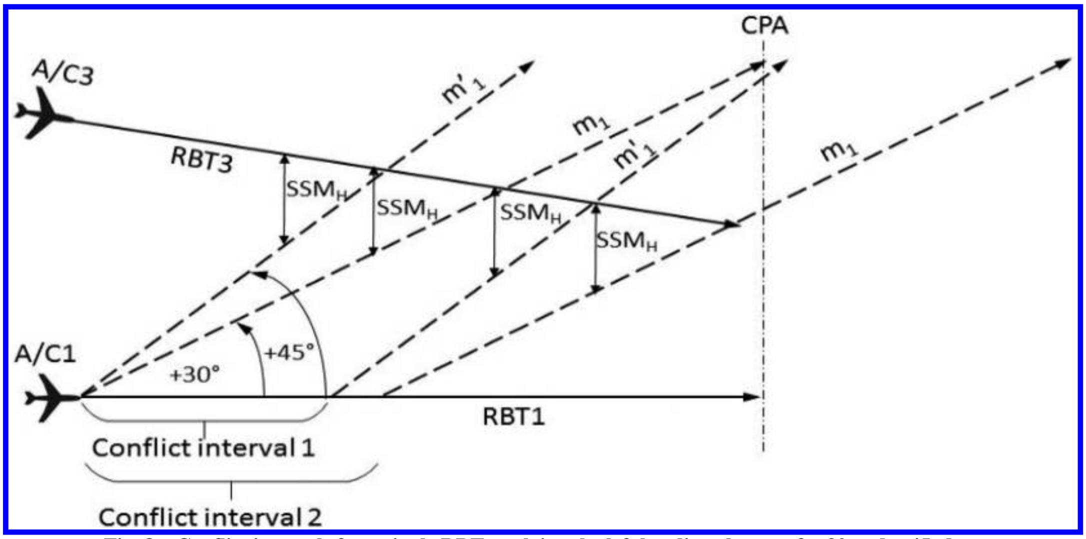

Fig. 8 Conflict intervals for a single RBT applying the left heading change of +30 and +45 deg.

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three aircraft A/C1, A/C2, and A/C3 is presented in Table 1. In general, an STI could comprise one or more maneuvering combinations.

The maneuvering combination in Table 1 denotes the combination of maneuvers of two aircraft. Generally, t_{Sk} represents the starting moment of the kth conflict interval, and t_{Ek} is its ending moment, $k = 1, \ldots, I$. The conflict intervals have different durations, depending on the trajectory geometries and combinations of the avoidance maneuvers.

IV. Rate of Reduction in the Number of Amendment Solutions

Once all the conflict intervals are generated, it is possible to compute the total number of conflict amendments. As previously stated, the algorithm applies the checking/sampling time rate of 1 s (i.e., $p = 1$ s). However, this parameter is configurable. For higher aircraft speed ranges or closure rates in the encounters, p can assume lower values (for instance, 0.5) as the aircraft dynamic states are subject to different types of the trajectory deviations [32]. If LAT is determined by the beginning and ending time instants (i.e., t_{IN} and t_{CPA}, respectively), $\forall t_{\mathrm{Sk}} \in [t_{\mathrm{IN}}, t_{\mathrm{CPA}})$, $\forall t_{\mathrm{Ek}} \in (t_{\mathrm{IN}}, t_{\mathrm{CPA}}]$, and the number of conflict amendments at a random time threshold t is given by

$$C_A(t) = \frac{M^{(N_A-2)}}{p} \sum_{k=1}^{I} [t_{\mathrm{Ek}} - \max(t_{\mathrm{Sk}}, t)] \tag{4}$$

where I denote the total number of conflict intervals within the ecosystem. The theoretical number of the ecosystem maneuvers for a given set of aircraft at instant t is computed as

$$\mathrm{TM}_A(t) = \frac{M^{N_A}}{p}(t_{\mathrm{CPA}} - t) \tag{5}$$

where t_{CPA} represents the time instant at the CPA. At each time instant, C_A is counted at a system level, meaning that if one aircraft induces a conflict with another one by its amending maneuver, the ecosystem is considered conflicting in that moment. Finally, the total number of amendment solutions at instant t is defined as the difference between $\mathrm{TM}_A(t)$ and $C_A(t)$:

$$S_A(t) = \mathrm{TM}_A(t) - C_A(t) = \frac{M^{(N_A-2)}}{p}\left(M^2(t_{\mathrm{CPA}} - t) - \sum_{k=1}^{I}[t_{\mathrm{Ek}} - \max(t_{\mathrm{Sk}}, t)]\right) \tag{6}$$

The maximum number of solutions $S_{A\max}$ is achieved in the moment of triggering of the ecosystem (i.e., $t = t_{\mathrm{IN}}$):

$$S_{A\max} = \frac{M^{(N_A-2)}}{p}\left(M^2(t_{\mathrm{CPA}} - t_{\mathrm{IN}}) - \sum_{k=1}^{I}[t_{EK} - t_{\mathrm{IN}}]\right) \tag{7}$$

$S_A(t)$ is characterized by a decreasing rate in the time evolution. This rate depends on the ecosystem size (number of aircraft), trajectory geometries, and configuration of the initial encounter. In theory, the decreasing rate of the ecosystem solutions can be approximated to an exponential decay with the number of amendment solutions (as a quantity) decreasing at a rate proportional to its current value (S_A):

$$\frac{\mathrm{d}S_A}{\mathrm{d}t} = -\eta S_A \tag{8}$$

where η denotes a coefficient known as the exponential decay constant. A solution from Eq. (8) is obtained as

$$S_A(t) = S_{A\max} e^{-\eta t} \tag{9}$$

However, real scenarios show that a loss of the amendment solutions cannot be described by the exponential decay function (i.e., η is not constant). Figure 9 illustrates a decreasing rate in the number of solutions over LAT in the case of two synthetic traffic scenarios. Scenario 1 illustrates the more-complex ecosystem comprising five aircraft members in different flight configurations (climb, cruise, descent), generating more STIs and fewer conflict-free solutions. On the contrary, scenario 2 presents a less-complex ecosystem containing three aircraft members in a stable (cruise) configuration, which provides more resolution capacity for different maneuvering combinations. Both scenarios are considered theoretical and representative for a simple comparison of the maximum resolution capacity (i.e., number of feasible solutions) in the ecosystem identification moments, their perishable behavior, and the reached deadlock moments.

Scenario 1 quantifies a higher ecosystem complexity than scenario 2 as the number of the amendment solutions drops more rapidly, especially in the first 60 s, and thereafter slightly slowly until 120 s.

Table 1 Example of the STI structure

STI number	Interdependent aircraft IDs	Maneuvering combination	t_S, s	t_E, s
STI_1	A/C1–A/C2	m_0–m_2	880.00	910.83
		m_2–m_4	872.00	905.24
		m_3–m_2	880.00	910.83
STI_2	A/C1–A/C3	m_0–m_0	859.00	1012.87
		m_3–m_1	972.00	1010.44
STI_3	A/C2–A/C3	m_0–m_1	884.00	912.90
		m_2–m_3	880.00	909.83
		m_4–m_2	884.00	912.90

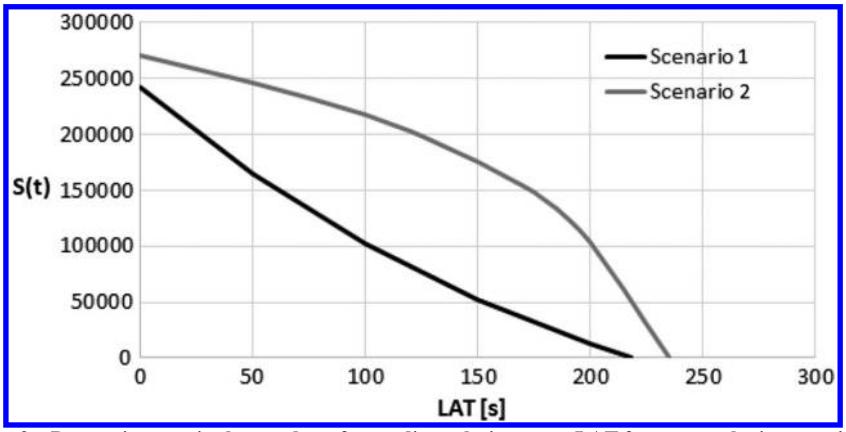

Fig. 9 Decreasing rate in the number of amending solutions over LAT for two synthetic scenarios.

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Table 2 Simulation properties

Simulation number	Properties				
	H_{CB}, n mile	V_{CB}, ft	DA, deg	VR, ft/min	FPA, deg
1	15	3000	$+30/-30$	$+1000/-1000$	$+2/-2$
2	15	3000	$+45/-45$	$+1500/-1500$	$+3/-3$
3	20	4000	$+30/-30$	$+1000/-1000$	$+2/-2$
4	20	4000	$+45/-45$	$+1500/-1500$	$+3/-3$

Furthermore, $S_A(t)$ for scenario 1 reaches the value of 0 earlier, indicating that aircraft will be more cooperative in negotiation before entering a severe and infeasible situation. The ecosystem members in scenario 2 have more amendment solutions, which explicitly includes a larger number of TWPs and, potentially, more conflict-free resuming segments. It can be observed that, in both cases, η is not constant. Owing to this fact and a high number of initial solutions ($S_{A\,\max}$), the simulation runs are a better option for the generation of results than the analytical computational method explained in this section.

V. Analysis of the Simulation Results

This section provides relevant results obtained from the simulations of the ecosystem model. Simulations have been performed within the LAT interval of 300 s. The objective is to compare N_A, and N_{STI}, in addition to C_A and S_A at different time instances. From a traffic sample, two conflict encounters (pairwise scenarios) have been selected, and the following cluster–ecosystem parameters have been applied to the simulation runs (Table 2).

Figures 10 and 11 graphically present the first and second encounters (encounter 1 and encounter 2, respectively), describing the RBT projections (geometries) of two aircraft in both planes.

Table 3 provides the simulation data for the two encounters, each generating four ecosystems.

Table 3 shows that, with standard cluster limits (simulation 1 and simulation 2), encounter 1 generates a larger ecosystem size than encounter 2 and, consequently, a higher number of interdependencies and conflict intervals. By increasing the cluster bounds (simulation 3 and simulation 4), N_A is increased for encounter 2, but N_{STI} and I exhibit different behavior. For encounter 1, reductions in N_{STI} and I between simulation 2 and simulation 3 demonstrate an improved maneuvering capacity but also indicate the ecosystem complexity in the first conflict intervals of the LAT. In the case of encounter 2, a similar fact is reflected between simulation 1 and simulation 2, but with an enlarged cluster volume, all the three properties are evidently characterized by extremely high values. Equation (3) is fully satisfied for all the simulation runs. Increased values of N_M and I with the duration of each conflict interval affect Eqs. (4–6), producing exponentially decreased trend of the amendment solutions. Figures 12 and 13 illustrate $S_A(t)$ for both encounters in each of the four runs.

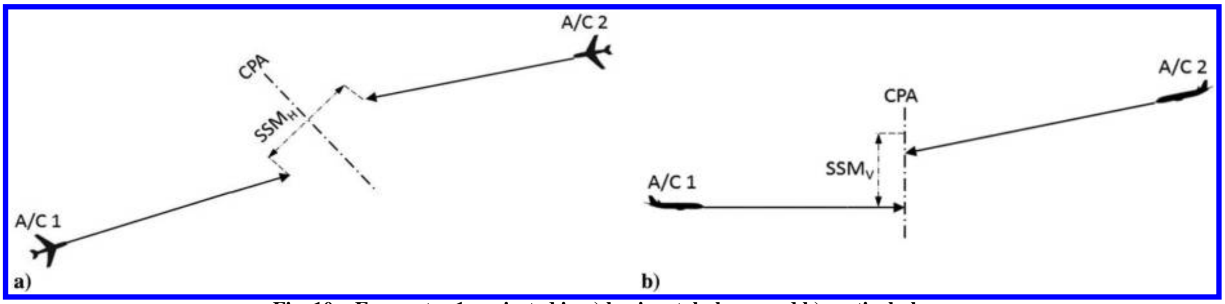

Fig. 10 Encounter 1 projected in a) horizontal plane, and b) vertical plane.

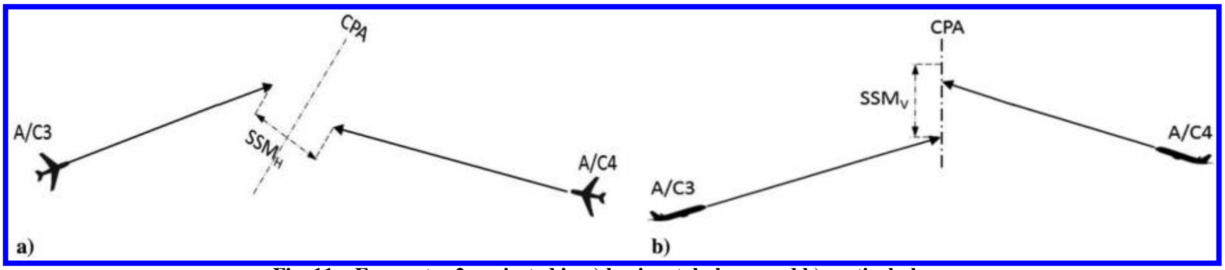

Fig. 11 Encounter 2 projected in a) horizontal plane, and b) vertical plane.

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Table 3 Simulated ecosystems for two selected encounters

	Encounter 1			Encounter 2		
Simulation number	N_A	N_{STI}	I	N_A	N_{STI}	I
1	7	17	90	4	4	13
2	8	22	110	3	3	14
3	8	21	93	9	24	163
4	9	25	117	9	22	166

The two ecosystems, obtained from simulation 1 and simulation 2 of encounter 2, respectively, have a lower complexity in applying amendments because their number of potential solutions decreases at a lower rate over LAT. Other ecosystems are characterized by very complex scenarios. The plots in Fig. 12 demonstrate that the rate of reduction can be drastically changed with the increased cluster–ecosystem parametric values. Thus, it is possible to make the following observations.

1) An ecosystem aircraft identifying nearby cluster bounds could be limited in the search space for its resolution because the surrounding nonecosystem aircraft could be potential threats for conflict-free maneuverability.

2) For complex scenarios, $S_A(t)$ reduces to zero in approximately 90–60 s before the CPA, indicating that members can easily enter the CA layer, forcing each other to perform a difficult resolution amendment (for instance, the heading change might be above 45 deg or climb above $+1500$ ft/min).

3) A higher drop in the number of solutions in the first 60 s requires early collaborative decision-making. This might demonstrate higher system optimality and feasibility when performing earlier conflict-free amendments.

Sensitivity in this study denotes a comparable distinction between the simulated ecosystem scenarios. Figure 12 illustrates a small distinction (higher sensitivity) as well as Fig. 13 for two pairs of ecosystems. For the same ecosystem size and slight difference in the geometry of the ecosystem trajectories, the structures of the spatiotemporal interdependencies might significantly differ that affect the resolution capacity over time and slope of the curve.

Further research on ecosystem resolutions will focus on a computational method for the resuming segments via the identification of TWPs and a definition of the modeling elements that could provide a

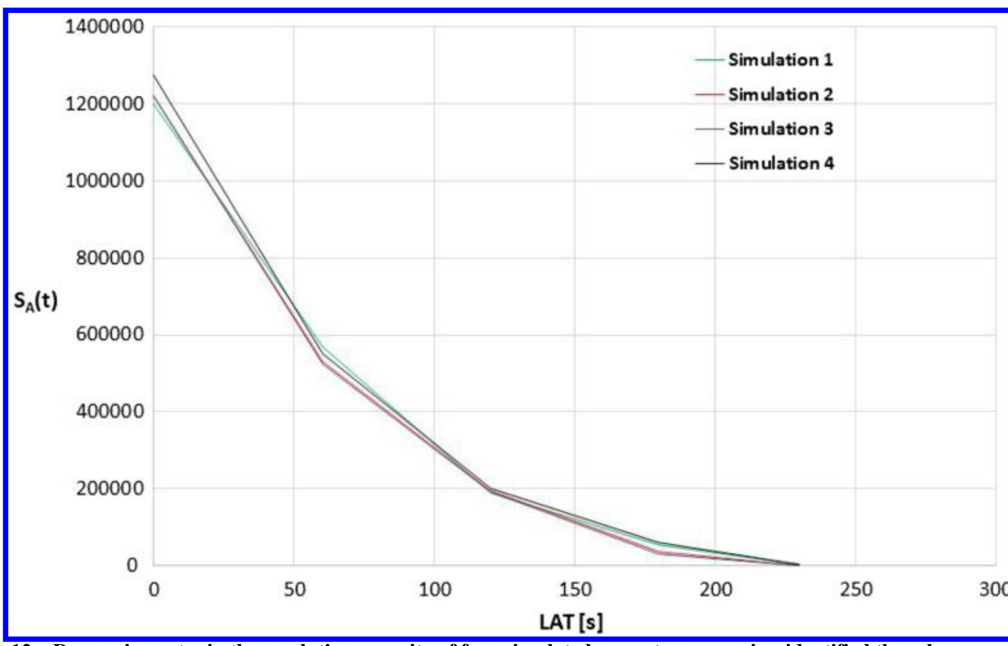

Fig. 12 Decreasing rates in the resolution capacity of four simulated ecosystem scenarios, identified though encounter 1.

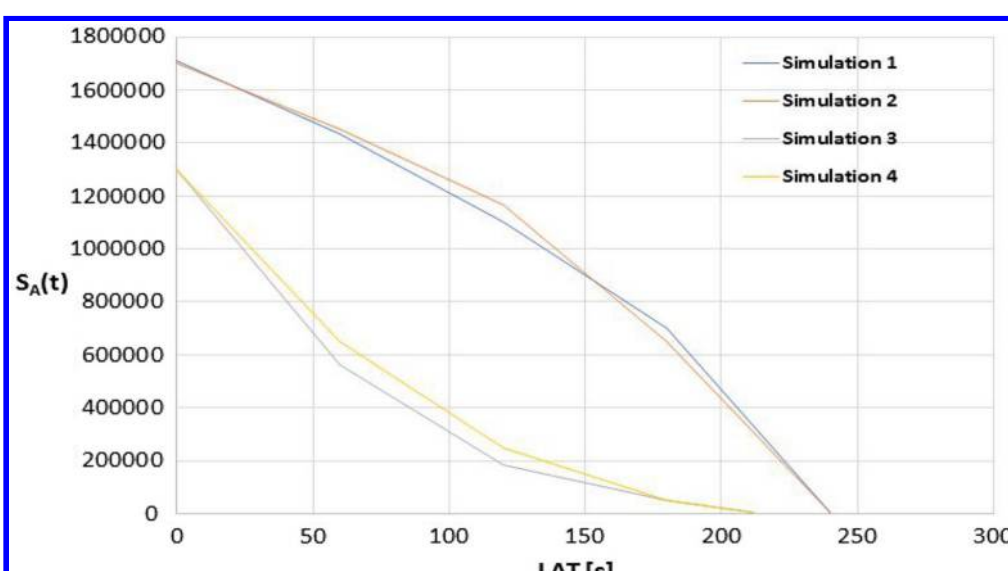

Fig. 13 Decreasing rates in the resolution capacity of four simulated ecosystem scenarios, identified though encounter 2.

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smooth transition from the conflict-free amendments. The main criterion in the combination of the ecosystem solutions will be feasibility rather than optimality. However, early decisions can guarantee the smallest resulting deviations from the RBTs. Generation of the complete resolution trajectories by the means of defined TWPs will provide a capability of measuring the total time for resolving all the conflicts, as a performance indicator. Nevertheless, the research will be extended to the analytical computation of a deadlock moment, in which at least one aircraft will stay out of a conflict-free solution.

VI. Conclusions

This paper relies on the previous research on the ecosystem creation algorithm, attempting to identify the complexity in the search space of amending conflict-free segments. The computational framework is based on the stepwise simulations of the cluster–ecosystem transitions using different identification parameters. It has demonstrated effectiveness in providing safe amendments at the operational level, when the severity of conflict situation increases rapidly. A decreasing rate between the available ecosystem resources and elapsed time, expressing a potential path in negotiations among the aircraft, indicates that each missed moment in reaching an agreement reduces the number of remaining viable amendments. The simulation results were obtained via the analysis of variable cluster–ecosystem properties. In addition to the standard cluster buffers and maneuvering amendments, the additional ones were introduced to obtain a better insight into the elaboration of the surrounding traffic. Finally, the results showed that the increased values can produce more complexity in the amendments and definition of the tactical waypoints for complete resolutions.

Acknowledgments

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J. Krozel
Associate Editor

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Appendix B: Scalable conflict management framework for air transportation

Radanovic M., Piera M.A. Scalable Conflict Management Framework for Air Transportation. Journal of Advanced Transportation (under review).

Scalable Conflict Management Framework for Air Transportation

Marko Radanovic[1] and Miquel Angel Piera Eroles[1]
[1]Department of Telecommunications and Systems Engineering, Autonomous University of Barcelona, Sabadell, 08202 Spain

Corresponding author: Marko Radanovic (e-mail: marko.radanovic@uab.cat).

ABSTRACT This study elaborates the conflict management framework of unmanned aerial vehicles, focusing on the application of smart vehicle connectivity technologies for the identification of the spatiotemporal interdependencies between unmanned aeronautical vehicles considering the scalability problem in high dense scenarios. This article seeks to justify the applied separation criteria among small cooperative unmanned aerial vehicles based on their performance characteristics and the planned mission type. The adopted criteria present the testing asset, referring to a current lack of spatiotemporal requirements and a need for performing more research in this area to provide a more rapid integration of these vehicles for passenger and freight transport purposes into the civil airspace. The article describes the computational framework for the conflict detection function and operational metrics for causal identification of the spatiotemporal interdependencies between two or more cooperative vehicles, treating them as a conflict mission system that strives to achieve an efficient solution by applying certain maneuvering measures before a loss of separation occurs. Urban mobility by means of Personal Aerial Vehicles (PAV’s) generates more pressure to design new mechanisms that could avoid separation minima infringements between vehicles. Simulation of five urban short-range missions illustrates the potential for time-based complexity analysis in the conflict resolution process.

INDEX TERMS conflict management framework, detect and avoid, spatiotemporal interdependencies, unmanned aerial vehicles.

I. INTRODUCTION

Vehicle connectivity has provided the baseline framework for the implementation of cooperative mechanisms to improve the traffic efficiency and safety indicators while providing relevant information to implement mitigation mechanisms. Automated guided vehicles (AGV’s) in indoor applications are an excellent example of a centralized cooperative mechanism issuing movement orders and clearances to AGV’s which behaves as obedient objects sharing location information. Air Traffic Management (ATM) is a management and control set of predefined activities to allow a safe and efficient air traffic, in which in which aircraft shares flight data and follow the directives of air traffic controllers (ATC’s) according to elaborated traffic information. Main difference between AGV’s and aircraft in ATM is scalability and environment. A reduced set of vehicles in a controlled environment (ie. AGV’s) pave the way for automation, while the coexistence of several vehicles competing for the same space (ie. ATM) in an un-predicted environment (ie. low visibility, wind perturbations) requires a human in the loop approach to react in front of un-predicted events.

Nowadays, ATM is facing a capacity problem to fit future traffic demand according to present automation level, and is designing new decentralized cooperative mechanisms relying on a more powerful aircraft connectivity to improve safety, and transport efficiency. The emerging of new urban mobility demand such as Personal Aerial Vehicles (PAV’s) or urban freight transport such as Remote Piloted Aircraft Systems (RPAS) generates more pressure for innovative systems to improve the quality of the transport services considering realistic environments in which any un-predicted vehicle maneuver can lead to a collision. As a result, it is recognized as an emerging research challenge in the air traffic management industry [1] the scalability problem to attend new transport demands while preserving safety and efficiency. The Federal Aviation Administration (FAA) has launched many projects related to small UAVs (sUAVs) to support their future deployment in the civil airspace and integration with commercial aviation [2]. However, introduction of UAVs into many national airspace systems invokes challenges to preserve the safety, capacity and efficiency of the current airspace. Many research studies have proposed the use of sUAVs operating at the low altitudes in environments that range from unpopulated farmlands to densely populated cities. While the commercial traffic in some of these environments is not extremely dense, new challenges arise from operations that require an aircraft to fly around people, buildings, terrain and man-made obstacles.

To accommodate the future demand for low-altitude sUAVs [3], previous air traffic management (ATM) experiences indicate that this demand must be organized to to balance efficiency and safety. Furthermore, it is necessary to have the systems in place to scale future traffic densities and the mixtures of different UAV types. Currently, general aviation, gliders, and helicopters operate in the low altitude uncontrolled airspace, i.e., airspace class G [4]. Accommodating new entrants in a safe manner with the existing airspace users is critical. There are many commercial UAV applications, such as cell phone tower inspections, that operate within the visual line of sight (VLOS). However, UAV operators demand to fly their missions beyond visual line of sight (BVLOS), where economic value is greater compared with the same missions (e.g., inspection of pipelines and deliveries) using conventional manned transportation, either in the air or on the ground. It is also expected that BVLOS UAV operations will require autonomous capabilities [5].

To safely integrate all manned aircraft operations with VLOS and BVLOS UAV operations in the low-altitude airspace, a systematic scale to quantify the diversity and future demand is necessary. National Aeronautics and Space Administration (NASA) envisioned this potential and initiated research into Unmanned Aerial System (UAS) Traffic Management (UTM) based on decades of ATM research and development experience [6]. As the sUAV industry, with its use cases and technologies, is rapidly evolving, the UTM concept and its equivalent in Europe, U-Space [7], evolves. U-Space is a set of new innovative services and specific procedures designed to support safe, efficient and secure access to airspace for large numbers of UAVs. Therefore, U-Space is not to be considered a defined volume of airspace that is segregated and designated for the sole use of UAVs. U-Space should ensure smooth UAV operations in all operating environments [8] and in all types of airspaces (particularly, but not limited to, very low-level airspace [9]). U-Space addresses the need to support all types of missions [10, 11].

Unfortunately, airspace operation performance and the integration requirements have not been developed to accommodate a large-scale mix of BVLOS UAV, VLOS UAV, and manned aircraft operations. NASA's research started with development of a concept of operations that defines how these operations in low-altitude airspace could be accommodated in a safe manner. Currently, UTM airspace is regulated but not controlled, which means air traffic control (ATC) services are not provided for routine operations. Hence, the main barrier to large-scale UAV operations is the lack of airspace systems requirements, procedures, and supporting functions [12]. There are many differences between manned aircraft operations and the envisioned UAV operations:

1. There is no pilot on-board the UAV to detect and avoid (DAA) other aerial vehicles.
2. There is a wide range of new and unknown UAV performance characteristics.

3. sUAVs often do not have the capability to carry heavy or power-intensive equipment.
4. The separation standards and requirements for UAV are very different than the conventional ATM requirements. The biggest risk is to the people and assets on the ground and to manned aircraft. Unlike civil manned aircraft, UAVs may fly very close to each other under certain circumstances, such as a high integrity level in positioning or under acceptable weather conditions.
5. The density of operations in the airspace could easily be several orders of magnitude higher than in case of manned aircraft operations. For example, the National Airspace System (NAS) currently experiences approximately 5000 flights at any given moment [13].

Many beneficial sUAV civil applications in low-altitude airspace have been proposed. Example applications include infrastructure monitoring (surveillance), precision agriculture, public safety, search and rescue, disaster relief, weather monitoring, and delivery of goods [14]. With respect to the listed applications, two types of the UAV missions could be distinguished: local or short-range missions applied to sUAVs and distance or delivery missions characterized for larger UAVs. The former type presents the mission with specific, task-based function, e.g., terrain surveillance or infrastructure monitoring, with certain performance characteristics and limitations. The mission type is usually characterized by a closed, polygonal profile, whose departing and ending points are usually near each other. The latter mission type is BVLOS, proposed for larger ranges and focusing on the time requirements [15], i.e., a delivery function (for example, goods delivery). Thus, the larger UAV types are considered with respect to the conditions in which they operate (higher altitudes, payload carrying on-board, etc.).

With the foreseen long-term integration into commercial/controlled airspace, any sUAV entering this area must be enhanced with smart technologies to meet strict requirements. One of these requirements is the ability to sense and avoid (SAA) potential conflicts [16]. This article describes the operational concept and methodology for the conflict detection and resolution framework in the multi-UAV environment for short-range missions. The methodology has been already applied to the tactical air traffic system [17], which considers a cluster of aircraft involved in a detected conflict by the means of identifying the spatiotemporal interdependencies (STI) among them. The objective is to solve the time horizon paradigm, i.e., the time criticality leading to a conflict or collision state through the cooperative aircraft interactions and the resolution decisions.

This paper provides the baseline for the design of future information systems and smart technologies to examine and apply the appropriate separation criteria to detect pairwise conflicts and maintain safety between the missions in a resolution phase. In addition to this introductory section, this paper contains five additional sections. Section II describes the safety layers for UAV conflict management. Section III explains the mission conflict management framework. Section IV presents the simulation results based on testing five local UAV missions and discusses the results from two conflict management systems in terms of their potential resolution. Concluding remarks and directions for the future work are provided in section V.

II. SAFETY LAYERS FOR UAV CONFLICT MANAGEMENT

The analyzed UAV conflict management framework is considered an evolution of the tactical and operational safety net of the present ATM system considering a Trajectory-Based

Operations (TBO) context [18], relying on a 4-D trajectory management approach, in which each point along the trajectory is defined by a 3-D position (i.e., latitude, longitude and altitude) and required timestamp to overfly. A predictability to reach each point at the required time of arrival is fully assumed without any uncertainties or deviations [19].

A. SAFETY NETS WITHIN ATM PLANNING LEVELS

Integration of the safety layers in commercial air traffic, ranging from trajectory management (TM) and separation management (SM) to collision avoidance (CA), has always been a challenging task. With the constant increment of the traffic demand and future integration of UAVs into the airspace system, this process is becoming more complex. In general, the aircraft SM function is allocated to the ATC system and is triggered by the conflict detection event that can be identified at two planning levels: strategic and tactical. Depending on the planning level, an appropriate resolution maneuver can be applied. The standard separation minima (SSM) for the loss of separation between two aircraft, either for conflict detection or maintenance of the resolution maneuver, is 5 nautical miles (NM) horizontally and 1000 feet (ft) vertically. Once the aircraft enter the conflict zone, the CA layer is activated, presenting the operational level in which an instantaneous maneuver is requested because of the time criticality. All three levels are referenced to the closest point of approach (CPA) between the two aircraft in conflict. CPA is an estimated 4-D point on the conflicting trajectories, at which a 3-D distance between the two aircraft reaches its minimum value.

The tactical level comprises the time interval from 15 minutes until 60 seconds before the CPA reachability. This layer is characterized by a certain look-ahead time for conflict detection in which an appropriate resolution strategy can be applied. This strategy usually refers to the definition of the tactical waypoints (TWPs) or tactical offset paths for amendment from the conflict segments that can be achieved by changes in the heading vectors or vertical rates in discrete moments. Finally, the operational level is determined by the CA zone of each aircraft that is triggered 45-50 seconds before the CPA and depends on the closure rate of the aircraft and flight levels and geometry of the encounter. In this phase, the collision avoidance system (CAS) logic that requires an instantaneous and, sometimes, hard avoidance maneuver is usually applied.

B. SEPARATION LEVELS APPLIED TO UAV FLIGHTS

Because of the different operational and performance characteristics of UAVs compared to manned aircraft as well as the remote position of a pilot, the conflict detection and resolution function is usually treated in two ways: SAA and separation assurance (SA) [20]. In the former case, SAA is related to collision avoidance, i.e., CA presents an SAA action to prevent another UAV from entering the collision zone when all other separation modes fail. In the latter case, SA denotes a self-separation capability that requires a longer look-ahead time to prevent CA activation while complying with the accepted air traffic separation standards.

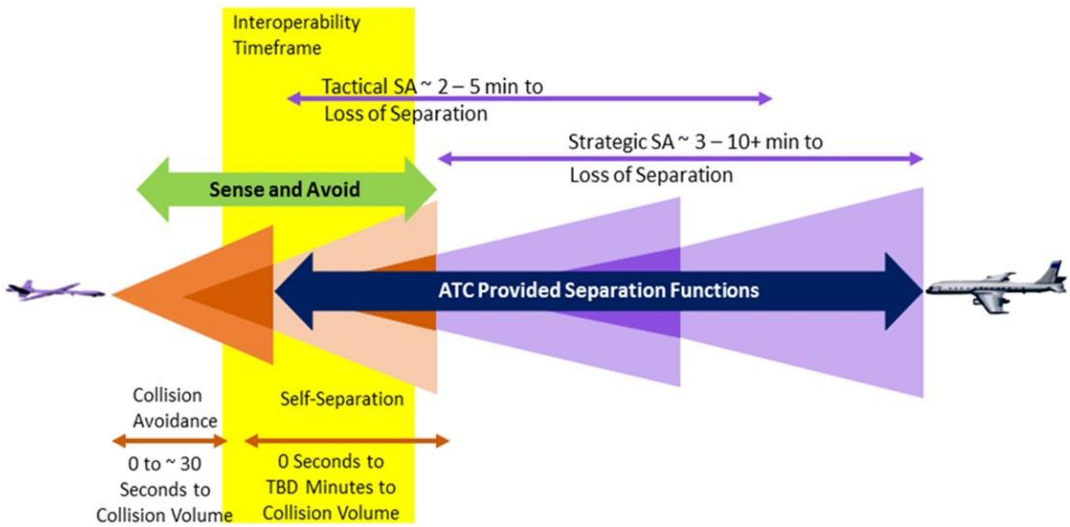

Figure 1: Separation levels for UAV flights

The UAV separation levels shown in Fig. 1, illustrates how the tactical SA is usually activated 2 to 5 minutes before one UAV enters the CA zone of another UAV, while the strategic SA is timely and framed from 3 to more than 10 minutes for a predicted loss of separation. For the interoperability timeframe, in which a manned aircraft could co-exist with an UAV, a resolution trajectory will be applied to the UAV enhanced with an overriding control, thus avoiding any potential maneuver by the manned aircraft.

The two separation levels covering the strategic and tactical safety layers are set as *controlled separation* and *remain well clear (RWC),* respectively. In this approach, there is a provision of a smooth transition to the tactical level operations that also has a significant impact on UAV mission planning, empowering a ground pilot's ability to "detect" instead of "sense" a conflict.

Taking into consideration the scalability of the future traffic demands with the VLOS and BVLOS UAV operations as well as the previously explained interoperability timeframe (i.e., the resolution maneuver always applied to the UAV), the controlled separation or ATC SM function might not be so relevant for future conflict resolution methodologies. Thus, future solutions will be more oriented to the RWC safety layer. The RWC interval synthesizes the DAA function supporting the tactical maneuvers (trajectory amendments) for conflict resolution [21]. Fig. 2 illustrates the DAA function within the RWC and CA layers.

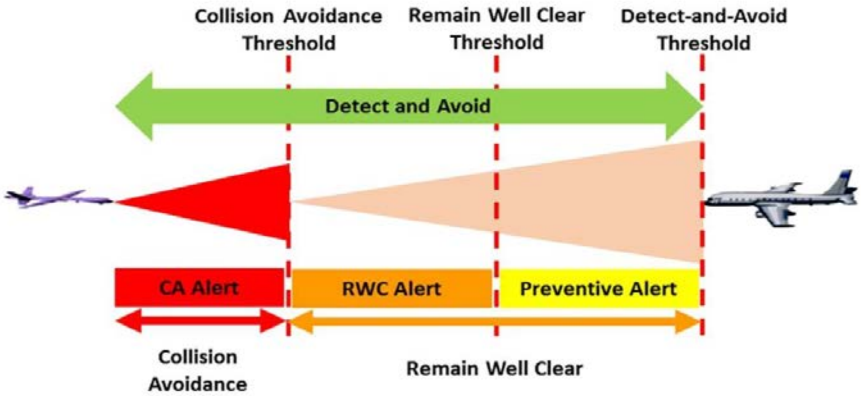

Figure 2 DAA function within the RWC and CA safety layers

Computation of the RWC threshold is important to guarantee the present safety levels. In the NAS [22], the conditional probability of a Near Mid-Air Collision (NMAC) risk for the RWC threshold in the UAV integration is considered. NMAC is defined using the Traffic alert and Collision Avoidance System (TCAS) standard as an event that occurs when the centers of masses of two aircraft pass less than 500 ft horizontally and 100 ft vertically [23]. In Fig. 2, the RWC threshold analogously separates the RWC layer into two sub-layers (similar to TA and RA TCAS signals): a *preventive alert,* which warns the UAV in conflict about a potential NMAC state, after which, the *RWC alert* is activated to warn the UAV about the severity of a relative dynamic state in approaching the CA threshold and computes an appropriate combination of the avoidance maneuvers. The separation criteria are evaluated with respect to the TCAS logic, accounting for the closure rates and time-based separation, rather than the spatially measured separation among a pair of the successive UAV positions. Although [22] presents a well-established background, there is still a lack of spatiotemporal requirements for the UAV separation criteria, and more research is needed before the CA layer can be activated. Moreover, the separation criteria should rely on the advanced look-ahead time (LAT) for the tactical resolution, modeling and planning of different mission types and the UAV performance-based category. This paper further explores these aspects by proposing the tested and applied separation minima (ASM) for cooperative missions. As an example, Fig. 3 illustrates a typical UAV mission projected in the horizontal plane.

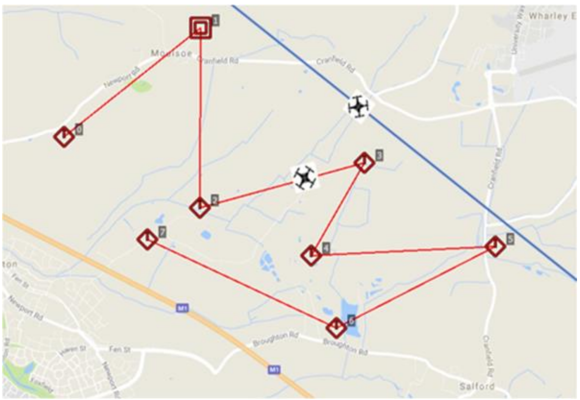

Figure 3: An example of a local UAB test mission with a closed trajectory profile

The closed mission profile does not allow smooth cooperative flights maintaining the NMAC separation criteria (500 ft horizontally and 100 ft vertically). Nevertheless, by applying the NMAC criteria, non-necessary alerting of the UAV pilot in situations where the RWC perishes would rapidly trigger a CA alert and request a compulsory avoidance maneuver. Therefore, the route spacing between local missions might be narrow, providing a possibility for exploring less conservative criteria. In doing so, a series of tests on planned missions were conducted using a wide range of the performance values.

C. MERIT TRANSITION TO SMALL UAV SEPARATION CRITERIA

To better identify the RWC threshold, several tests were performed for cooperative missions planning of 5-7 UAVs with the following performance characteristics:

- mass: < 25 kg,
- min. speed: 0 m/s,
- cruise speed: 10 m/s,
- max. speed: 20 m/s,

- max. climb: 10 m/s (at min. speed),
- nom. climb: 5 m/s,
- max. altitude: 100 m AGL (Above Ground Level),
- max. flight duration: 60 minutes.

As a result, it is validated that half of the values for the NMAC separation criteria avoid false positive and do not miss any separation minima infringements. Thus, the ASM criteria are taken to be 250 ft horizontally and 50 ft vertically. Fig. 4 describes the continuous profile of the inter-distances in time, expressed by the state (3-D) positions between the UAV pairs flying over their missions. Fig. 4a shows the profile observed using the separation criteria of 200 ft horizontally and 40 ft vertically, and Fig. 4b illustrates the same profile with respect to 250-50-ft separation criteria. In both cases, 3-D separation is expressed by a horizontal line (an offset to time axis).

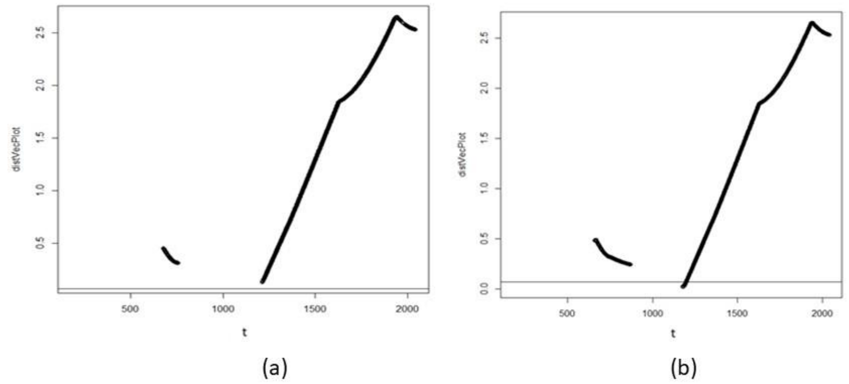

Figure 4: Profiles of the relative distances in time between the mission pairs, applying a separation of (a) 200-40 ft and (b) 250-50 ft.

If the profile at any time point overlaps with or intersects the 3-D separation line, two UAVs are considered to be in conflict, i.e., they generate a separation infringement with respect to a given criteria. In the case of 200-40 ft, the infringement does not occur, whereas in the case of 250-50 ft, the profile intersects the separation line, indicating that UAVs are in conflict within certain time interval (note that the time axis is scaled by a 500-seconds step). Any increment in the 3-D separation extends the conflict interval between UAVs. A discontinuity in the profile during certain time interval is found, indicating that the successive 3-D inter-distances of two UAVs in this period are quite large. Therefore, the applied separation metrics with respect to the NMAC criteria and mission profiles used for testing are 250 ft horizontally and 50 ft vertically (Fig. 5).

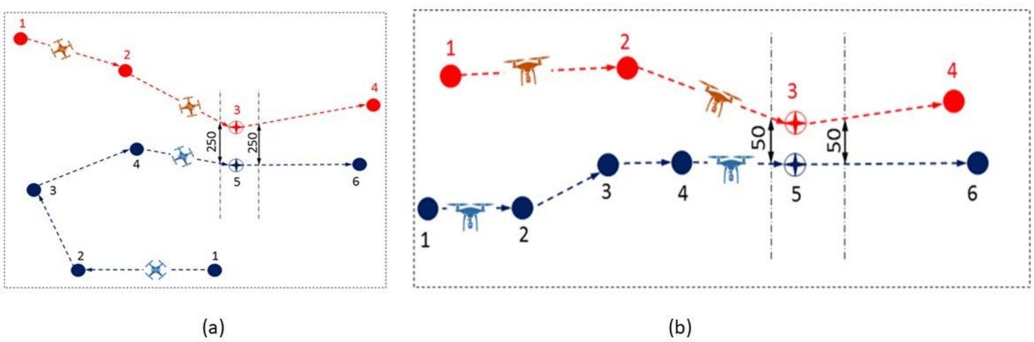

Figure 5: . ASM for the tested missions in (a) the horizontal plane and (b) vertical plane

III. MISSIONS CONFLICT MANAGEMENT FRAMEWORK

A. STATE-BASED CONFLICT DETECTION

The state-based conflict detection relies on the TBO concept, supporting 4-D mission inputs (latitude, longitude, altitude and timestamp) and the ASM criteria. Table I illustrates an example of the mission inputs.

UAV identifier	Latitude [deg]	Longitude [deg]	Altitude [ft]	Time [s]
UAV_1	52.07064334	-0.669822693	164.04	355
UAV_1	52.05713493	-0.669908524	295.28	612
UAV_2	52.05106538	-0.638751984	229.66	1476
UAV_2	52.04436151	-0.671539307	131.23	2264
UAV_3	52.06600028	-0.667161942	98.43	663
UAV_3	52.06009025	-0.663385391	131.23	1047

Table 1: EXAMPLE OF INPUT MISSIONS DATA

The point altitudes at the mission planning level are usually given in meters-AGL, presenting relative values with respect to the Mean Sea Level (MSL). Although this paper does not analyze the static obstacles and terrain configuration, the generated values are converted to feet (ft) and added to the elevation of each overflown mission waypoint (WP) to obtain the absolute altitude values.

A predictability to reach each point at the required time of arrival is fully assumed without any uncertainties or deviations. Present analysis can be extended with trajectory uncertainties, leading to more conservative results. A projected linearity over the projected horizontal and vertical mission profiles is fully assumed, which presents the shortest segment length between two WPs. Considering the UAV state positions and velocity information derived from the 4-D flight plans as well as the closure rates between them, the algorithm is based on Euclidean state-based conflict detection. Because the input data are provided as geographic coordinates (Table I), i.e., latitude (φ), longitude (λ) and altitude (h), those coordinates are transformed into the Euclidean 3-D space (x, y, z). The most common and widely used approach is the stereographic projection, which is a particular mapping or function that projects a sphere onto a plane [24]. The transformation equations for a sphere of radius R are given by:

$$\begin{aligned} x &= k \cos\varphi \sin(\lambda - \lambda_0) \\ y &= k[\cos\varphi_0 \sin\varphi - \sin\varphi_0 \cos(\lambda - \lambda_0)] \\ z &= h \end{aligned} \qquad (1)$$

where λ_0 is the central longitude, φ_0 is the central latitude, and the coefficient k can be expressed in the following form:

$$k = \frac{2R}{1 + \sin\varphi_0 \sin\varphi + \cos\varphi_0 \cos\varphi \cos(\lambda - \lambda_0)} \qquad (2)$$

Therefore, after the transformation $\lambda \rightarrow x$, $\varphi \rightarrow y$, $h \rightarrow z$ and the corresponding conversion into the required units, i.e., x and y to [NM] and z to [ft], it is possible to implement the conflict detection algorithm for the analyzed traffic scenario. Once transformed, the input 4-D points belonging to each trajectory have the form WP [x, y, z, t].

Implementation of the Euclidean state-based conflict detection algorithm simplifies the methodology referring to the case of two UAVs in conflict, namely, A and B [25]. Their states are described by positions S_A and S_B, respectively, and their velocity vectors are denoted by V_A and V_B, respectively. The position projections of A along the axes are denoted by S_{Ax}, S_{Ay} and S_{Az}, and the projections of its velocity vector are denoted by V_{Ax}, V_{Ay} and V_{Az}, respectively. Each UAV is surrounded by an imaginary volume, called a protected zone. This protected zone defines a minimum separation distance between UAVs. The protected zone in a 3-D space takes a shape of a flat cylinder with diameter D and height H. Therefore, the imaginary cylinder around A is defined by a set of points (X, Y, Z) satisfying the conditions:

$$\sqrt{(X-S_{Ax})^2+(Y-S_{Ay})^2} < \frac{D}{2} \qquad (3)$$

$$|Z-S_{Az}| < \frac{H}{2} \qquad (4)$$

The minimal separation distance is considered as ASM, i.e., $ASM_H = D/2 = 250$ ft, and $ASM_V = H/2 = 50$ ft. In a general context, the protected zone of A is defined as a set of points, P_A, that satisfy:

$$P_A = \{X \mid \| S_A - X \| < \frac{1}{2}\} \qquad (5)$$

where || . || denotes a norm vector. In the case of a cylinder of diameter D and height H, the norm is defined as:

$$\|(X,Y,Z)\| = \max\left(\frac{\sqrt{X^2+Y^2}}{D}, \frac{|Z|}{H}\right) \qquad (6)$$

Using the previous expression, the norm can be calculated as a distance between UAVs, that potentially results in a loss of the ASM. The distance between A and B is defined as:

$$\Delta(A,B) = \| S_A - S_B \| \qquad (7)$$

The separation between A and B is reduced if and only if $\Delta(A, B) < 1$. One of the assumptions for the state-based conflict detection function (CDF) is linearity. At a future time-instant t, the state prediction A(t) from the current position can be expressed as:

$$S_A(t) = S_A + tV_A \qquad (8)$$

$$V_A(t) = V_A \qquad (9)$$

CDF continuously predicts a loss of separation between A and B within LAT, i.e., in an advanced time of 200 seconds that corresponds to the tactical separation assurance (Fig. 1). A and B are in conflict if there is a predicted instant t at which an achieved distance between them will be less than 1:

$$\Delta(A(t), B(t)) < 1 \qquad (10)$$

Once the conflict is detected, the algorithm outputs the starting conflict points (CP_1 and CP_2); it also calculates their CPAs (CPA_1 and CPA_2) and the ending conflict points (CP'_1 and CP'_2) by searching their 3-D positions along the missions at a one-second sampling rate. However, the objective is to provide coherent resolutions to the conflicting UAVs before entering the CA layer, which practically means that avoidance maneuvers must be performed at any instant inside the RWC layer, from the conflict prediction points (PP_1 and PP_2) until the starting conflict points (CP_1 and CP_2). Fig. 6 illustrates an example of two UAVs approaching each other in a level flight. The figure denotes the conflict thresholds for the RWC and CA layers and describes an available space in which an avoidance maneuver should be performed.

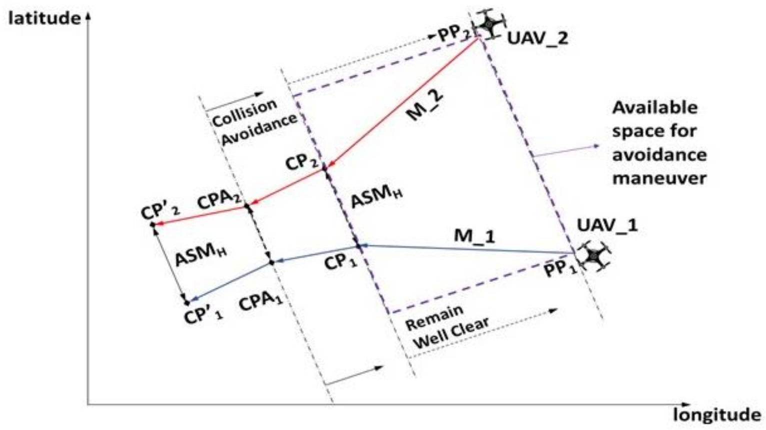

Figure 6: . The RWC and CA thresholds in a pairwise encounter and the available space for the avoidance maneuvers.

B. SPATIOTEMPORAL INTERDEPENDENCIES

To provide a time-sufficient resolution capacity and avoid induced collisions or downstream problems, it is necessary to explore the nearby space. Once a conflict between two UAVs is detected, each of them explores its proximate space in which a certain solution can be found, with the goal of not inducing any conflict with other UAV(s) flying in its proximity. This state space analysis generates STIs. STIs are characterized by the induced conflict(s) that can be generated by the certain maneuver(s) and the conflict intervals. Any maneuver not producing new conflict(s) is treated as a potential solution, and the parts of the nearby airspace volume are considered as conflict-free. A UAV affected by the avoidance maneuver of the conflicting aircraft is defined as a surrounding UAV. The conflicting UAVs together with the surrounding UAV(s) form a conflict mission system (CMS) that strives to achieve a smooth and coherent resolution and resume the missions' task. The 3-D separation criteria, as in the case of the initial conflict, remain in place.

Therefore, the STI algorithm determines all members of the conflict missions' system to be surrounding UAVs for which the loss of ASM with any of two conflicting UAVs would occur if this UAV performs a given avoidance maneuver at any moment during LAT. Maneuverability is applied in both the horizontal and vertical planes using a certain set of parametric values to identify the surrounding UAVs that should be considered to be members of the conflict mission system:

- m_1: left heading change with a deflection angle of +30°,
- m_2: right heading change with a deflection angle of -30°,
- m_3: climb at a vertical rate of +1 m/s,
- m_4: descent at a vertical rate of descent of -1 m/s.

In this paper, the holding capability of a sUAV (at a minimal speed of 0 m/s) is not considered to preserve compatibility with the fixed-wing UAV. The main assumption in this research is the cooperative conflict resolution. Therefore, a single avoidance maneuver that reacts to the conflict event is not assumed to be proper. Rather, a pair of maneuvers is required, keeping in mind the principle of equity among UAVs in performing the cooperative task. Fig. 7 describes an example of an avoidance maneuver applied in both the horizontal and vertical planes and, also depicts the induced conflict intervals generated by those maneuvers, providing the starting (t_S) and ending (t_E) conflict instants.

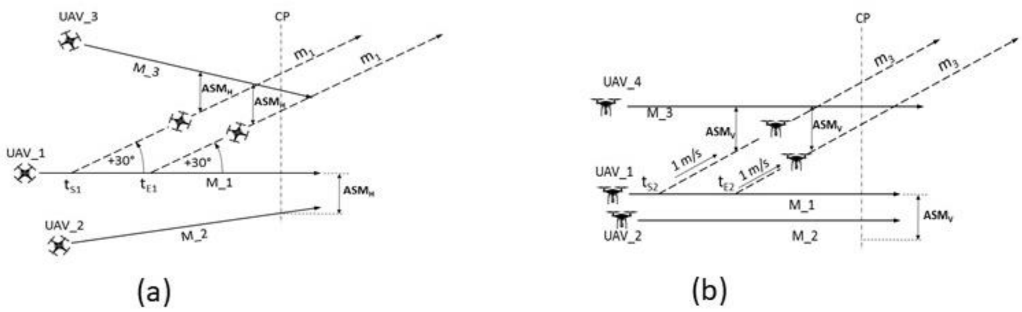

Figure 7: Conflict Mission System generated by potential avoidance maneuvers in (a) the horizontal plane and (b) vertical plane

STIs are formalized by a combination of 3 elements (refer to Table V in section IV):

- *interdependent UAV identifiers*: a pair of UAVs maneuvering in a proximate airspace
- *maneuvering combination*: a pair of maneuvers that would lead to a new separation minima infringement;
- *conflict interval*: a time interval during which the pair or maneuvers would lead to this infringement.

IV. SIMULATION RESULTS

This section provides relevant results obtained from a simulation of five testing missions with the cooperative surveillance task. The mission plans were generated in APM Planner 2.0 [26]. The UAV type used for simulation has the same performance characteristics as previously listed in this paper. Table II provides the input points for each simulated mission, and Fig. 8 describes the mission profiles covering a certain region. The missions take a polygonal shape with a short range, and the planned flight time is less than 60 minutes.

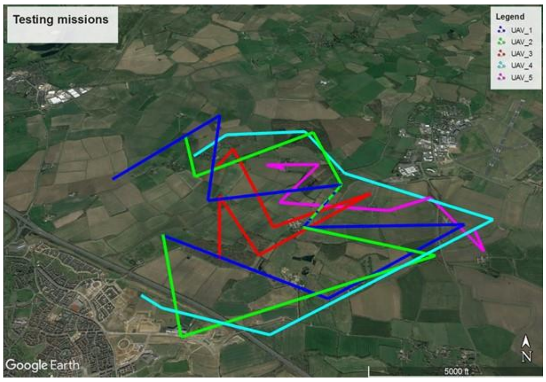

Figure 8:Lateral profiles of the tested missions

The developed CDF has two outputs - pairwise conflicts, namely, UAV_2 – UAV_3 and UAV_2 – UAV_4, at different time instances with no surrounding UAV(s). The shots shown in Fig. 9 describe the profiles of the conflicting UAVs and localize the positions of detected conflicts. The plots shown in Fig. 10 illustrate the profiles of the relative distances in time between UAVs with respect to ASM.

UAV identifier	Latitude [deg]	Longitude [deg]	Altitude [ft]	Time [s]
UAV_1	52.062465	-0.686560	0.00	0
UAV_1	52.070643	-0.669823	164.04	355
UAV_1	52.057135	-0.669909	295.28	612
UAV_1	52.060512	-0.649738	98.43	1001
UAV_1	52.053546	-0.656261	328.08	1183
UAV_1	52.054232	-0.633688	262.47	1613
UAV_1	52.048109	-0.653172	65.62	2002
UAV_1	52.054760	-0.676346	65.62	2461
UAV_2	52.069008	-0.675917	0.00	60.00
UAV_2	52.061726	-0.672827	131.23	189
UAV_2	52.067214	-0.653687	196.85	674
UAV_2	52.060512	-0.649738	98.43	822
UAV_2	52.053546	-0.656261	328.08	1027
UAV_2	52.051065	-0.638752	229.66	1476
UAV_2	52.044362	-0.671539	131.23	2264
UAV_2	52.054760	-0.676346	82.02	2431
UAV_3	52.064101	-0.669994	0.00	300
UAV_3	52.066000	-0.667162	98.43	663
UAV_3	52.060090	-0.663385	131.23	1047
UAV_3	52.055393	-0.660381	98.43	1414
UAV_3	52.057399	-0.646219	328.08	1728
UAV_3	52.050907	-0.662270	295.28	2385
UAV_3	52.058824	-0.668535	164.04	2824
UAV_3	52.052385	-0.667934	16.40	3138
UAV_4	52.065736	-0.673857	0.00	125
UAV_4	52.068322	-0.668535	98.43	368
UAV_4	52.068005	-0.654974	131.23	795
UAV_4	52.061937	-0.649052	98.43	1051
UAV_4	52.054127	-0.630083	328.08	1598
UAV_4	52.043728	-0.660725	295.28	2404
UAV_4	52.046684	-0.674372	164.04	2832
UAV_4	52.048796	-0.677977	16.40	3037
UAV_5	52.063942	-0.658579	0.00	40
UAV_5	52.062940	-0.661497	164.04	145
UAV_5	52.061621	-0.653343	295.28	366
UAV_5	52.058454	-0.659437	98.43	541
UAV_5	52.055341	-0.644073	328.08	923
UAV_5	52.057399	-0.637379	262.47	1112
UAV_5	52.052649	-0.630941	65.62	1295
UAV_5	52.055235	-0.631199	65.62	1340

Table 2: Example of Input Missions Data

Table III provides the available spaces for avoidance maneuvers for both CMS. The available space is expressed as a time-based box-shaped volume with its vertices combining the latitude, longitude, altitude and time limits. Table IV presents the obtained STIs, i.e., the maneuvers that cannot be performed inside the available space. Therefore, the available spaces cover the RWC layer before the UAVs reach the collision state, and provide the dimensions for the resolution capacity in time for applied avoidance maneuvers.

Conflict identifier	Interdependent UAV identifiers	Time limits [s]	Latitude limits [deg]	Longitude limits [deg]	Altitude limits [ft]
Conflict 1	UAV_2-UAB_3	649	52.06010071	- 0.66765577	92.34
Conflict 1	UAV_2-UAB_3	849	52.06561039	- 0.65083870	190.21
Conflict 2	UAV_2-UAB_4	464	52.06512433	- 0.66829345	108.43
Conflict 2	UAV_2-UAB_4	664	52.06834956	- 0.65398823	195.12

Table 3:4D Limits of the available space for avoidance maneuvers

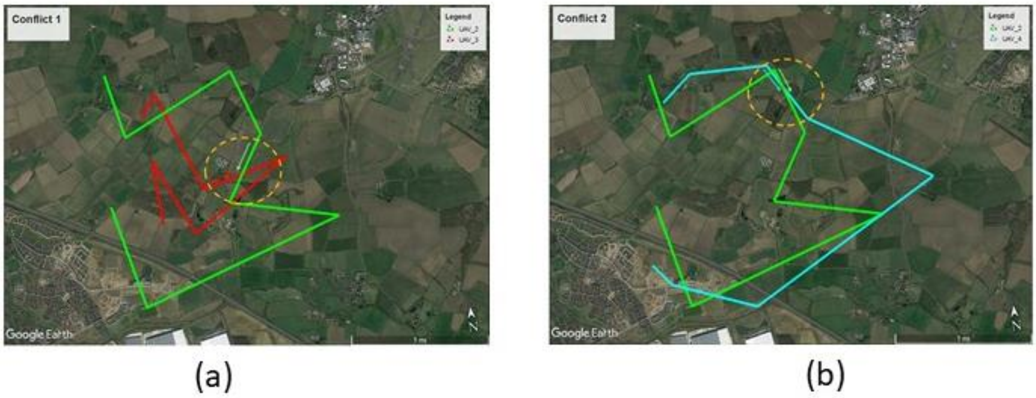

Figure 9: . Horizontal conflicting mission projections of (a) UAV_2 with UAV_3 (Conflict 1) and (b) UAV_2 with UAV_4 (Conflict 2).

STI identifier	Interdependent UAV identifiers	Maneuvering combination	Conflict interval [s]
STI_1	UAV_2 – UAV_3	$m_2 - m_1$	651 – 836
STI_1	UAV_2 – UAV_3	$m_3 - m_3$	649 – 849
STI_1	UAV_2 – UAV_3	$m_4 - m_4$	656 – 848
STI_2	UAV_2 – UAV_4	$m_2 - m_0$	464 – 573
STI_2	UAV_2 – UAV_4	$m_0 - m_1$	464 – 571
STI_2	UAV_2 – UAV_4	$m_2 - m_1$	464 – 498
STI_2	UAV_2 – UAV_4	$m_3 - m_0$	464 – 552
STI_2	UAV_2 – UAV_4	$m_0 - m_4$	567 – 660

Table 4: STI's Generated by each conflict mission system

Finally, any combination of the listed maneuvers applied at a time point that does not belong to the given conflict intervals or any of the non-listed combinations of maneuvers applied within the existing conflict intervals provides coherent, conflict-free resolution in the case of both CMS. Nevertheless, Table V illustrates some of the potential solutions.

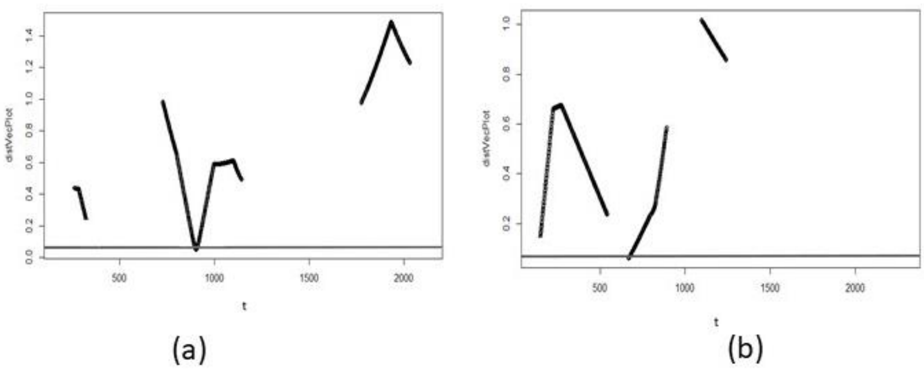

Figure 10: Profiles of the relative distances in time with respect to applied separation minima between (a) UAV_2 and UAV_3 and (b) UAV_2 and UAV_4.

STI identifier	Interdependent UAV identifiers	Maneuvering combination	Conflict interval [s]
STI_1	UAV_2 – UAV_3	$m_1 - m_1$	651 – 836
STI_1	UAV_2 – UAV_3	$m_3 - m_4$	649 – 849
STI_1	UAV_2 – UAV_3	$m_4 - m_4$	649 – 655
STI_2	UAV_2 – UAV_4	$m_2 - m_3$	464 – 573
STI_2	UAV_2 – UAV_4	$m_1 - m_0$	464 – 571
STI_2	UAV_2 – UAV_4	$m_4 - m_1$	464 – 498
STI_2	UAV_2 – UAV_4	$m_3 - m_0$	553 – 664
STI_2	UAV_2 – UAV_4	$m_0 - m_4$	464 – 566

Table 5: Avoidance Maneuvers Applied to the conflict mission system Resolutions

V. CONCLUSION

Mobility is at the beginning of a new revolution, which argues for safe drive-less vehicles cooperating for a more efficient traffic. The lessons learnt in commercial air traffic management in which high levels of automatisms have been achieved to support pilots, together with aircraft broadcasting information while flying to support a more smooth traffic is not enough to support an efficient use of the airspace for passenger and freight mobility. The irruption of PAV's in the near future and its mass adoption requires new frameworks to preserve separation minima.

This article presents the details of a novel operational framework to support strategic and operational decisions in the future design of automated traffic management for unmanned aerial vehicles. The main objective is to provide a seamless and operationally efficient transition between the safety nets when the severity of the conflict event evolves, which is significant because a continuous increase in traffic queries leads to situations in which infringements of the separation minima in highly dense airspace sectors frequently occur.

Achieved results provides the baseline to implement a cooperative/competitive multi agent system framework for a decentralized control of the air space capacity in urban areas. Further research to integrate the strategic decision making when accepting transport missions and the operational decision making when solving conflicts is under consideration as a promising mechanism to mitigate downstream conflicts due to local conflict resolutions.

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List of acronyms

3-D	three dimension
4-D	four dimension
ABMS	agent-based modeling system
ADS-B	automatic dependent surveillance-broadcast
ACAS	airborne collision avoidance system
ASM	airspace management
ATC	air traffic control
ATFCM	air traffic flow and capacity management
ATS	air traffic services
ATM	air traffic management
AU	airspace user
CA	collision avoidance
CDM	collaborative decision-making
CDR	conflict detection and resolution
CNS	communication, navigation, surveillance
CPA	closest point of approach
CR	conflict resolution
DAG-TM	distributed air/ground traffic management
DST	discrete event system
DST	decision support tool
E-TCAS	enhanced traffic-alert and collision avoidance system
FAA	Federal Aviation Administration
FL	flight level
ft	feet
ICAO	International Civil Aviation Administration
LAT	look-ahead time
MAS	multi-agent system

MTCD	mid-term conflict detection
NASA	National Aeronautics and Space Administration
NextGEN	Next Generation Air Transportation System
NM	nautical mile
RA	resolution advisory
RBT	reference business trajectory
RPA	remotely piloted aircraft
SESAR	Single European Sky ATM Research
SM	separation management
SSA	self-separating airspace
ST	surrounding traffic
STCA	short-term conflict alert
STI	spatiotemporal interdependency
TA	traffic advisory
TBO	trajectory-based operation
TCAS	traffic-alert and collision avoidance system
TM	trajectory management
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UTM	UAS traffic management