Universitat Autònoma de Barcelona

Spatio-Temporal Regions in the Context of Aircraft En-route Tactical Conflict Resolution

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Doctoral Thesis

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Summary

Air Traffic Management (ATM) is envisioned to change drastically in order to accommodate the increasing demand. For the strategic time horizon, that spans up to 2050, two lines of thoughts are presented. One of them supports a move towards non-controlled airspace and the concept of free flight. The other one seeks to move towards the opposite direction, that of fully automated, controlled airspace. Beyond their conceptual differences, both visions manifest some common components. The necessity for automatic tactical, en-route Conflict Detection & Resolution (CD&R) is one of them. Although the topic of CD&R has been heavily investigated the last three decades, several issues have not been treated by the literature. In particular, the proposed solvers do not exhibit some level of resilience, they do not provide a complete identification of the surrounding traffic that might be affected by the resolution of the original conflict, they do not allow airspace users to be involved in the Conflict Resolution (CR) in a realistic way in order to achieve efficient resolutions, and they do not provide the maneuver time limits within which feasible resolutions can be achieved. This work addresses the above issues in the following manner. The use of spatio-temporal regions instead of unique trajectories is proposed in order to achieve some level of resilience in the CR. Through the proposed "bottleneck" method, the regions' level of resilience is quantified. The so called "aerial ecosystem", the formal construct that serves to achieve complete identification of the relevant surrounding traffic, is formally defined in order to extend the CR with the completeness property. An analysis of historical and projected traffic in order to identify the size of the formed aerial ecosystems is performed. Pairwise conflict detection is used to construct a full aerial ecosystem. In order to treat cases when several pairwise conflicts co-exist in time with tight spatial bounds, the "aerial ecosystem" concept is extended and the "compound ecosystem" is defined. Moreover, some strategies to mitigate the dependence between the pairwise conflicts within the compound ecosystem are proposed. An analysis of historical and synthetic traffic is performed in order to identify the compound ecosystems that are formed and test the effectivity of the proposed mitigation strategies. An automated negotiation mechanism, through which airspace users can actively participate in the CR process is adopted. The proposed mechanism is decentralized, provides completeness of the identification process, and offers some level of resilience. In such a manner, airlines can participate in the CR with

the purpose of increasing efficiency without revealing their preferences regarding their costs and strategies. The automated negotiation mechanism is enriched by an initial approach to identify the temporal fences of the delegated aircraft pairwise conflict resolution framework. This information is used to determine the deadline for the automated negotiation procedure.

Resumen

Para hacer frente a la creciente demanda de uso del espacio aéreo, se esperan cambios drásticos en la presente Gestión del Tránsito Aéreo (ATM). Existen 2 líneas de pensamiento que agrupan las diferentes alternativas para un horizonte de tiempo estratégico, que se extiende hasta 2050. Una se basa en un movimiento hacia el espacio aéreo no controlado y el concepto de vuelo libre. La otra busca moverse hacia la dirección opuesta, la del espacio aéreo totalmente automatizado y controlado. Más allá de sus diferencias conceptuales, ambas visiones manifiestan algunos componentes comunes. La necesidad de una detección y resolución de conflictos táctica (CD&R) automatizada en ruta es una de ellas.

Aunque el tema de CD&R ha sido investigado a fondo en las últimas tres décadas, existen varios aspectos que no han sido tratados. En particular, las soluciones propuestas no exhiben cierto nivel de resiliencia, no proporcionan una identificación completa del tráfico circundante que podría verse afectado por la resolución del conflicto original, no permiten que los usuarios del espacio aéreo participen en la Resolución de Conflictos (CR) de manera realista (para lograr resoluciones eficientes), y no proporcionan los límites de tiempo de maniobra dentro de los cuales se pueden lograr resoluciones factibles.

Este trabajo aborda los problemas anteriores de la siguiente manera.

Se propone el uso de regiones espacio-temporales en lugar de trayectorias únicas para lograr cierto nivel de resiliencia en la CR. A través del método propuesto de "cuello de botella", se cuantifica el nivel de resiliencia de las regiones.

El "ecosistema aéreo", la construcción formal que sirve para lograr la identificación completa del tráfico circundante relevante, se define formalmente, para dotar al CR de la propiedad de sistema completo. Se realiza un análisis del tráfico histórico y proyectado para identificar el tamaño de los ecosistemas aéreos formados.

La detección de conflictos por parejas se utiliza para construir un ecosistema aéreo completo. Para tratar casos en los que coexisten varios conflictos pares en el tiempo con estrecha dependencia espacial, se amplía el concepto de "ecosistema aéreo" y se define el "ecosistema compuesto". Además, se proponen algunas estrategias para mitigar la dependencia entre los conflictos por parejas dentro del ecosistema compuesto. Se realiza un análisis del tráfico histórico y sintético para identificar los ecosistemas compuestos que se forman y probar la efectividad de las estrategias de mitigación propuestas.

Se adopta un mecanismo de negociación automatizado, a través del cual los usuarios del espacio aéreo pueden participar activamente en el proceso de CR. El mecanismo propuesto es descentralizado, proporciona la integridad del proceso de identificación y ofrece cierto nivel de resiliencia. De esta manera, los usuarios pueden participar en el CR con el propósito de aumentar la eficiencia sin revelar sus preferencias con respecto a sus costes y estrategias.
El mecanismo de negociación automatizado se enriquece con un enfoque inicial para identificar los límites temporales del marco de resolución de conflictos por parejas de la aeronave delegada. Esta información se utiliza para determinar el límite temporal para el procedimiento de negociación automatizado.

Resum

Es preveu que la Gestió del Trànsit Aeri (ATM) canviï dràsticament. Per a satisfer la creixent demanda d'ús de l'espai aèri, s'esperen canvis dràstics en la present Gestió del Trànsit Aeri (ATM). Per l'horitzó de temps estratègic, que s'estén fins al 2050, Existeixen 2 línies de pensament que agrupen les diferents alternatives per a un horitzó de temps estratègic, que s'estén fins al 2050. Una es basa en un moviment cap a l'espai aeri no controlat i el concepte del vol lliure. L'altre busca moure's cap a la direcció oposada, la de l'espai aeri totalment automatitzat i controlat. Més enllà de les seves diferències conceptuals, ambdues visions manifesten alguns components comuns. La necessitat d'una detecció i resolució de conflictes tàctica (CD&R) automatitzada en ruta és una d'elles.
Tot i que el tema de CD& R ha estat investigat a fons en les últimes tres dècades, existeixen diferents aspectes que no han estat tractats. En particular, les solucions proposades no mostren cert nivell de resiliència, no proporcionen una identificació completa del tràfic circumdant que podria veure's afectat per la resolució del conflicte original, no permeten que els usuaris de l'espai aèri participin en la Resolució de Conflictes (CR) de manera realista (per aconseguir resolucions eficients), i no proporcionen els límits de temps de maniobra dins dels quals es poden aconseguir resolucions factibles.
Aquest treball aborda els problemes anteriors de la següent manera.
Es proposa l'ús de regions espacio-temporals en lloc de trajectòries úniques per aconseguir cert nivell de resiliència en la CR. A través del mètode proposat de "coll d'ampolla", es quantifica el nivell de resiliència de les regions.
L' "ecosistema aeri", la construcció formal que serveix per aconseguir la identificació completa del tràfic circumdant rellevant, es defineix formalment per dotar al CR de la propietat de sistema completEs realitza una anàlisi del tràfic històric i projectat per a identificar la dimensió dels ecosistemes aeris formats.
La detecció de conflictes per parelles s'utilitza per construir un ecosistema aeri complet. Per a tractar casos en els quals coexisteixen diferents conflictes parells en el temps amb estreta dependencia espacial, s'amplia el concepte "d'ecosistema aeri" i es defineix l' "ecosistema compost". A més, es proposen algunes estratègies per a mitigar la dependència entre els conflictes per parelles dins de l'ecosistema compost. Es realitza una anàlisis del tràfic històric i sintètic per a identificar els ecosistemes compostos que es formen i provar l'efectivitat de les estratègies de mitigació proposades.
S'adopta un mecanisme de negociació automatitzat, a través del qual els usuaris

de l'espai aèri poden participar activament en el procés de CR. El mecanisme proposat és descentralitzat, proporciona la integritat del procés d'identificació i ofereix cert nivell de resiliència. D'aquesta manera, els usuaris de l'espai aèri poden participar en el CR amb el propòsit d'augmentar l'eficiència sense revelar les seves preferències respecte dels seus costos i estratègies.
El mecanisme de negociació automatitzat s'enriqueix amb un enfocament inicial per a identificar els límits temporals del marc de resolució de conflictes per parelles de l'aeronau delegada. Aquesta informació s'utilitza per a determinar el límit temporal per al procediment de negociació automatitzat.

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Contents

Publications, Conferences & Summer Schools

Journal Articles

- Koca Th., Piera M.A., and Radanovic M. - A Methodology to Perform Air Traffic Complexity Analysis based on Spatio-Temporal Regions constructed around Aircraft Conflicts. IEEE Access, 2019, 11 July 2019, 104528 –104541, DOI: 10.1109/ACCESS.2019.2928355.
- Koca Th., Piera M.A., and Radanovic M. - Constructing Safe Continuous Space-Time Regions for Air Conflict Resolution. IEEE Transactions on Intelligent Transportation Systems, (under review).
- Koca Th., and Piera M.A. - Air Spatio-Temporal Region Negotiation to Support Tactical Conflict Resolution Between Aircraft. Transportation Research Part C: Emerging Technologies (under review).
- Koca Th., Piera M.A., Radanovic M., and Nosedal Sanchez J. - Enhancing a delegated aircraft pairwise conflict resolution framework by the identification of temporal fences. Transportation Science (under review).

Conference Articles

- de Homdedeu J., Tous M. de M., Piera M.A., Koca Th., Radanovic M. - A Comperative Analysis of Different Methods for Identification of the Evolution of Number of Possible Conflict-Free Airspace Configurations Including Multiple Aircraft and Single Conflict. The 29th European Modeling & Simulation Symposium, September 2017. Barcelona, Spain.
- Koca Th., Piera M.A., and Radanovic M. - Design of a Multi-Agent System framework for Decentralized Decision Making in Air Traffic Management. ENRI International Workshop on ATM/CNS, November 2017. Tokyo, Japan.
- Koca Th., and Piera M.A. - A Multi-Agent System for Decentralized Airborne Conflict Resolution. IV Simposio CEA de Modelado, Simulacíon y Optimizacíon, January 2018. Valladolid, Spain.

- Koca Th., and Piera M.A. - Guarantying consistency of spatio-temporal regions that solve air traffic conflicts. EUROSIM2019, July 2019. Logroño, Spain.
- Koca Th., Isufaj R., and Piera M. A. - Strategies to Mitigate Tight Spatial Bounds Between Conflicts in Dense Traffic Situations. 9^{th} SESAR Inovation Days, December 2019. Athens, Greece.

Summer Schools and Study Groups

- Self-Organized Networks. 131^{th} European Study Group with Industry, May 2017. Bilbao, Spain.
- 19^{th} European Agent Systems Summer School, August 2017. Gdansk, Poland.
- 20^{th} European Agent Systems Summer School, June 2018. Maastricht, the Netherlands.

Chapter 1

Introduction

The earliest traces of people trying to fly can be found in the form of legends. In Greek mythology there is the myth of Daedalus and Icarus [1], and in Persian mythology there is the myth of Kay Kavus [2]. Some millenniums later, on December 17, 1903, the Wright brothers made the first successful powered, controlled and sustained airplane flight. The oldest continuously operated airline, KLM, was founded 13 years later, in 1919. It was initially operating flights between London and Amsterdam [3]. A century later, ICAO reports 37.8 million worldwide departures, during 2018 only [4].
In order to make such traffic volume possible some order needs to be imposed. In this research, safety and efficiency has been considered the driving forces behind such an order.

1.1 Safety

Air transportation can be hazardous[1]. Such an attribute has, unfortunately, illustrated itself various times through history [6]. To tackle the issue we would ideally seek to regulate air transportation in a way, that no hazardous states can arise. Given that such a regulation cannot be designed, aviation, as other risk bearing industries, has turned towards "risk management". ICAO defines "risk management" to be the systematic application of management policies, procedures and practices to the tasks of: establishing the context of, identifying, analyzing, evaluating and treating risks; monitoring the implementation of treatments; and communicating about risk [7]. A generic term representing the level of risk which is considered acceptable in particular circumstances is the "Target Level of Safety" (TLS) [8]. Risk management's goal is to keep the probability of hazardous events under the TLS.
Given the above, we can define safety to be the state in which the possibility of harm to persons or property damage is reduced to, and maintained at or below,

[1] By hazard here we mean any condition, event, or circumstance which could induce a harmful effect [5]

an acceptable level through a continuing process of hazard identification and risk management [9].

1.2 Efficiency

To make air transportation possible, among other tasks, we need to allocate part of the airspace to aircraft in order to perform their flights. This allocation, beyond being safe, needs to be also efficient. To discuss efficiency in this context, we should first acknowledge the existence of various, involved stakeholders. In the context of this work two stakeholders are relevant, regulators and airspace users, in particular airlines.

Five categories of Key Performance Indicators (KPIs) the regulators are interested in, can be found in EUROCONTROL's annual report [10]. The five categories are traffic, safety, capacity, environment, and cost-efficiency. Within them various KPIs to be optimized are present, some of which need to be minimized and others maximized. They include the total amount of flights within ECAC area, the growth compared to previous years as well as a future projection, the number of occurred accidents, the growth of capacity, the evolution of delays, en-route efficiency, and the Air Navigation Services[2] costs.

Airlines are entities that use the airspace to offer transportation. They are also concerned about safety, cost-efficiency, environmental impact, and social value. However, they do so with a local perspective, i.e. they are mostly interested in the performance of their own flights. Therefore, for each of their flights, they are interested to obtain the roots that optimize their performance. In terms of costs once they are en route, that translates to search of a balance between fuel consumption and schedule adherence [11].

Two competing companies, during the flights of their aircraft can compete for parts of the same airspace. Furthermore, an allocation of the airspace that might desirable for a regulator, might not be satisfactory for some of the involved airlines. It is evident that the involved parties may differ on their interests. Moreover, as earlier discussed, the same party can measure its performance by measuring several, distinct aspects of an allocation. Such situations are the object of study of Game Theory [12].

At the impossibility of defining a one dimensional function that accounts for the interests of all involved parties, various solution concepts are defined. Nash Equilibrium [13], probably the single most well-known concept within Game Theory, is formulated as the rational solution that involved parties should choose, given that they do not want to cooperate between them. Pareto Efficiency [14], is another solution concept. A possible allocation of resources is considered Pareto efficient if it is better than all the other possible allocations to which it can be compared to. It is a solution concept applicable in situations where involved parties are willing to collaborate.

A different wave of approaches intents to formulate a global objective function, known as welfare function [15]. In such conditions, the allocation problem is

[2] Defined in section 1.3.

treated as a constrained optimization problem.
Therefore, efficiency can be treated in two ways. We might let different individual parties to try and reach solutions between them. In doing so, their behavior can vary from purely collaborative to extremely competitive. On the other hand, efficiency can be treated in an aggregated manner, where the interests of all agents are considered through a welfare function. In this thesis we allow different entities interact through a negotiation process and try to reach Pareto optimal solutions.

1.3 Services Required for a Safe & Efficient Air Transport System

The order required to make the current traffic volume possible is imposed through Air Traffic Management (ATM). Formally, ATM is defined to be the dynamic, integrated management of air traffic and airspace safely, economically and efficiently, through the provision of facilities and seamless services in collaboration with all parties and involving airborne and ground-based functions [16]. It stands as one of the five broad families of services that make air transportation possible. The other four being Communication, Navigation, and Surveillance (CNS) services, Search And Rescue (SAR) family of services, Aeronautical Information Services (AIS), and METeorological services for air navigation (MET) [17]. The totality of all five families of services, is known as Air Navigation Services (ANS). A schematic representation of ANS is provided in Fig. 1.1.

On the other hand, ATM is composed of three main sub-classes of ser-

Figure 1.1: ANS is made up of five families of services.

vices [16]. Through Airspace Management (ASM) structure is imposed over the airspace, while through Air Traffic Flow Management (ATFM) en route aircraft are grouped into flows. In Europe, ATFM has evolved to become Air Traffic Flow and Capacity Management (ATFCM) [18]. While the purpose of ATFM is to avoid overloads in parts of the airspace, the purpose of ATFCM is double-fold. It seeks to avoid overloading, while making sure that the capacity is fully exploited[3]. Air Traffic Services (ATS) provide decision making, or advisory services, based on the collected information, and the established structures.

ATS is itself composed by Alerting Service (AS), Flight Information Service (FIS), and Air Traffic Control service (ATC) [16]. AS is the service provided to

[3]Efficient use of capacity is of vital importance in a dense airspace like the European one.

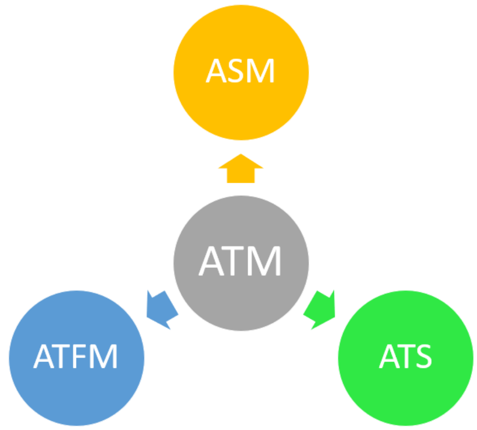


Figure 1.2: ATM is made up of several sub-families of services.

notify appropriate organizations regarding aircraft in need of search and rescue. FIS is the service provided for the purpose of giving advice and information useful for the safe and efficient conduct of flights, such as information regarding aerodromes, and possible hazards to flight. Lastly, ATC is the service provided to prevent collisions, and expedite and maintain an orderly flow of air traffic.

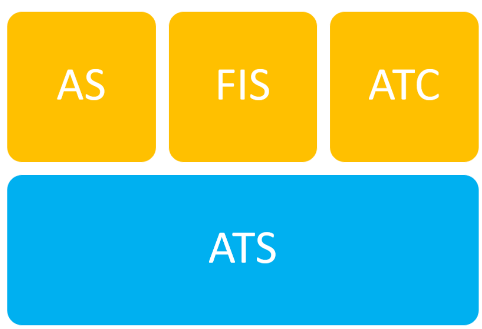


Figure 1.3: ATS is made up of three services.

1.4 Service Time Horizons in ATM

ATM services are offered at different time horizons and with respect to various reference events. The broadest time horizon within ATM is the strategic time horizon. Strategic time horizon has a length that can very from several years down to several days before the day of operation. Deciding over the airspace structure that will be used is an example activity performed at strategic time horizon. Pre-tactical time horizon is the time span of a day before, up to the day of operation [16]. An example of an activity performed during this time horizon includes the actions taken to adapt ATFCM based on the weather forecasts, the information received from the Flow Management positions at every ATC center in Europe, etc. Tactical time horizon spans from twenty, down to one minute, during the day of operation. An example of an activity performed at tactical level is separation management[4]. In this case the reference event is the potential loss of separation[5]. Lastly, operational time horizon, the shortest among them, spans up to one minute before the event of interest. A typical example concerning this time horizon is en-route collision avoidance. The event of interest in this case is the occurrence of the Closest Point of Approach (CPA).

1.5 FIRs, CTA, and ATC Sectors

The largest regular airspace division in use today is Flight Information Region (FIR). FIRs are regions within which FIS and AS need to be provided [19]. There is no standardization regarding the size of FIRs, however, each state is responsible to provide ANS within their airspace (and therefore also FIS and AS) [17]. This has lead to an airspace configuration, where a single FIR does not generally[6] cover more than a single country. Nonetheless, there are several approaches to divide airspace into FIRs. Small states, with low traffic volume (e.g. Albania), use a single FIR to cover their airspace, while in other countries several FIRs can coexist horizontally. A frequent practice is to make a vertical division of the regions, too. FIRs on the lower flight levels are still named FIRs, while the ones on the higher flight levels are renamed Upper flight Information Regions (UIRs). As illustrated in Fig. 1.4, there exist cases when within one country there are more FIRs than UIRs (e.g. France).

Within FIRs and UIRs there are Controlled Areas (CTAs). A CTA is a controlled airspace extending upwards from a specified limit above the earth [19]. Controlled Airspace itself is an airspace of defined dimensions within which ATC service is provided in accordance with the airspace classification[7].
CTAs are composed of air traffic control sectors. As EUROCONTROL ATM online glossary defines it, an ATC sector is a region for which an associated controller (or controllers) has ATC responsibility.

1.6 ATCo responsibilities

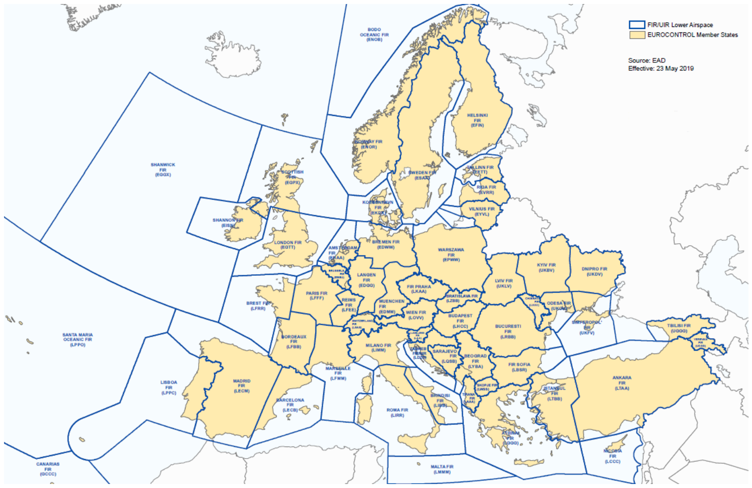
Currently, in Europe each sector has a pair of responsible controllers, the executive controller and the planner [3]. Cook [3], summarizes the responsibilities of each. The main responsibilities of the planner are:

[4] Defined in section 1.9.

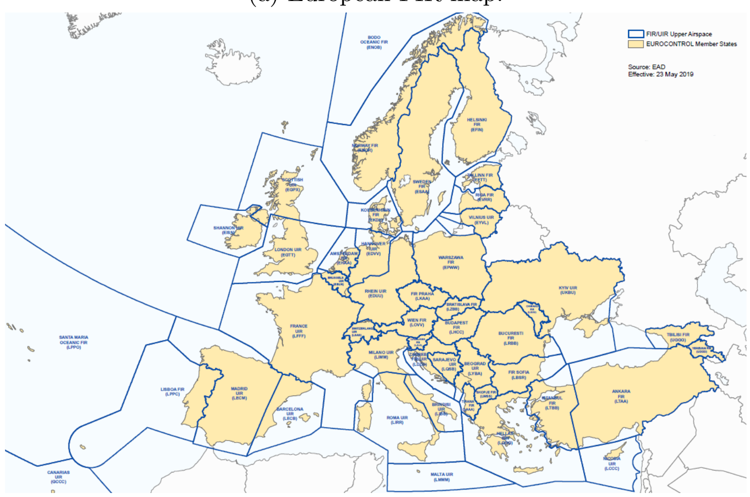
[5] Defined in section 1.9.

[6] Unless special agreements are achieved.

[7] ICAO defines various airspace classes [20]. Within each one of them different ATS are provided.



(a) European FIR map.



(b) European UIR map.

Figure 1.4: Flight Information Regions over Europe. Adapted from EUROCONTROL's FIR/UIR in the Lower/Upper Airspace maps, published on 32.05.2019.

- To coordinate and approve the entry and exit of flights into the sector, and identify the aircraft that are subject to its jurisdiction.
- To manage, classify, and keep up to date the strips[8][9].

[8] Controllers become aware of any new aircraft that enters, or is going to enter, their sector by means of the "control" strip. These strips are created automatically some minutes before the aircraft enters the sector.

[9] Note that Cook includes also the printing of the stripes in his original summary. However, nowadays most of the control centers use digital stripes.

- To make any flight data corrections in the Flight Data Processor (FDP)[10].
- To identify flight paths which are least likely to generate potential conflicts as flights progress in the sectors
- To monitor any additional frequencies, such as the emergency frequency

On the other hand, the executive controller is mainly responsible to:

- Take care of the "front-line" RT communication with the pilots.
- Accept the aircraft into the sector.
- Monitor their progress.
- Attain separation management.
  This implies he is also responsible to detect possible conflicts and issue instructions to eliminate them.
- Achieve the exit conditions set by the associated planning controller.

1.7 The Capacity Problem

Saez Nieto [21] states that the main bottleneck, in high density areas, in the current ATM system, is the large amount of tactical interventions, involving time pressure for controller's actions. This, he further reasons, limits airspace capacity[11] and safety, resulting in a lack of ATM efficiency, and limiting future air traffic growth.
Indeed, EUROCONTROL, in its annual 2018 report [10], announces a 3.8% increment of the number of IFR[12] flights, compared to 2017. Moreover, future projections predict a further increase for the years to come[13], as illustrated in Fig. 1.5. In the meantime, during 2018 only, overall en-route ATFM delays were incremented by 108% compared to 2017, to reach a total of 19 million minutes of delay, or 1.74 minutes of delay per flight. The report communicates capacity attributed delays to remain the main source of en-route ATFM delays, causing the 37.4% of them. These numbers clearly indicate the "the en-route capacity crisis"[14].

[10] In each ATC unit, the flight plan data of all aircraft that are planned to flight through, are stored in the FDP.

[11] Capacity is defined to be the maximum number of aircraft that can be accommodated in a given time period by the system or one of its components (throughput) [22].

[12] ICAO defines two types of flight rules, Visual Flight Rules (VFR) and Instrumental Flight Rules (IFR) [19].

[13] These projections did not take into account the COVID-19 crisis.

[14] The phrase is also used in the EUROCONTROL's 2018 annual report [10].

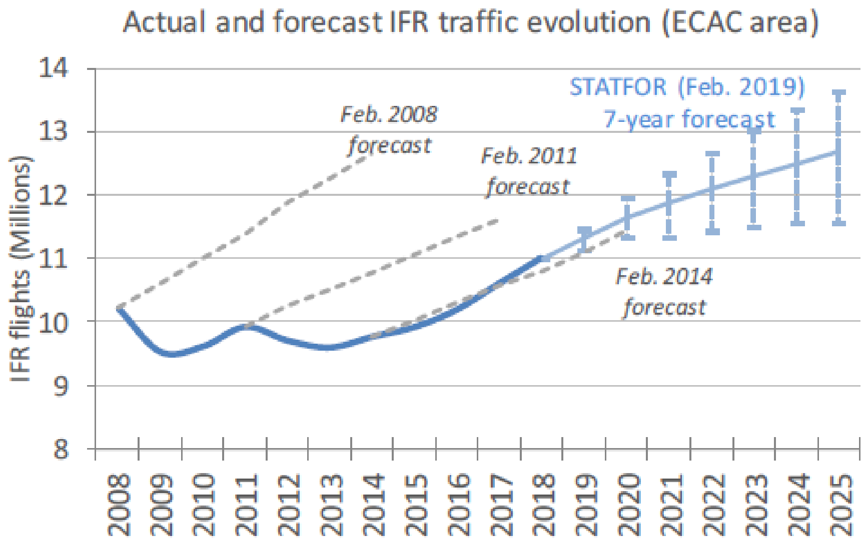


Figure 1.5: Actual and forecast IFR traffic evolution in the ECAC area. Reprinted from EUROCONTROL's Performance Review Report 2018.

1.8 Solution Directions for the Capacity Problem

We can state that the main goal of research in the field of ATM is to organize traffic in a manner that is safe, cost-efficient, environmentally friendly, and socially valuable [23,24]. Under the current circumstances, an increase of capacity in European airspace is mandatory. However, such increase cannot come at the cost of decreasing the current safety levels, environment impact, nor social value. Therefore new Paretto frontiers need to be explored. Within ATS, various new concepts are proposed to tackle the issue. As Saez Nieto notes [21], on a strategic time horizon[15] there are two main lines of thought that encompass these concepts. One of them supports a move towards non-controlled airspace and the concept of free flight. The other one seeks to move towards the opposite direction, towards a fully automated controlled airspace. The Trajectory-Based Operations (TBO) concept [25] is an example of a solution that leans towards the fully automated controlled airspace. The main idea behind is that all involved stakeholders will share accurate information. This information can then be used to modify the flight's planned and actual trajectory, before or during flight, if necessary.

Apart from their conceptual differences, both lines manifest common compo-

[15]The presented vision extends up to 2050.

nents. Conflict Detection & Resolution (CD&R)[16] lies among them. Potential conflicts, i.e. potential loss of separation, can arise no matter what paradigm ATM is built on. Therefore, a mechanism, automatic or not, to handle them will remain of vital importance. Nowadays, over European airspace, intervention to prevent the occurrence of potential conflicts is a responsibility of the tactical ATCo [3, 21]. However, the non-controlled airspace claims no ATCo, while the fully controlled airspace claims full automation. These imply that CD&R is among the tasks that needs to be automated in order to make any of the two realizable.

Moreover, SESAR includes tactical CD&R, in its 2020 European ATM Master Plan [26]. For manned aircraft, the conversion of the airspace to fully dynamic and optimized is listed among the essential operational changes that need to be made. In this context, the improved distribution of separation responsibility in ATC, and advanced CD&R tools for high densities, are listed among the key R&D activities to be performed.

1.9 CD&R

At a tactical time horizon, en-route safety is quantified through separation management. Separation management intents to maintain a minimum pairwise separation distance between aircraft. A loss of the required minimum separation is called a conflict [27].

In a scenario where a conflict could arise, the potential conflict should be detected and some trajectory amendment has to be issued in order to avoid it[17]. This process is known as Conflict Detection & Resolution (CD&R). Kuchar and Yang [28], provide a concise, schematic representation of a CD&R process, at tactical level. They decompose CD&R into three sub-processes. Conflict prediction is the first among them. Communication of the detected conflict to the human ATCo is the second one. The last process, is the process of assisting in the resolution of the conflict[18]. The organization of the phases of all three sub-process are shown in Fig. 1.6.

The environment, i.e. the airspace, needs to be monitored and information regarding its current state needs to be collected using various sensors. The collected information needs to be also disseminated, through communication channels. Further, dynamical models are utilized to project the current state to potential future states. These predictions, combined with some already developed metrics[19], can be used to achieve some informed decision-making within the context of ATM. Specifically, in case a loss of separation is predicted, the

[16] Defined in section 1.9.

[17] In case a potential conflict is a false positive and it is confirmed on time, no amendments are necessary.

[18] In systems where fully automated CD&R is implemented, the third sub-process should resolve the actual conflict.

[19] An example of a relevant metrics is the predicted minimum pairwise separation.

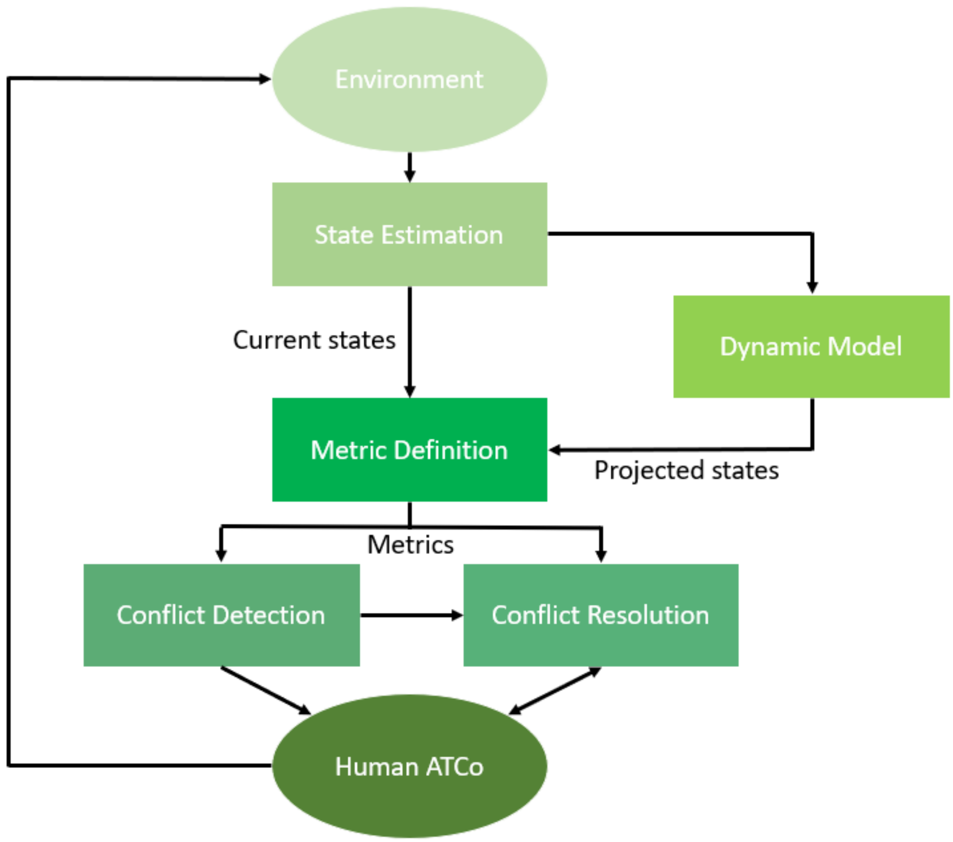


Figure 1.6: Schematic Representation of a CD&R process, as given by Kuchar & Yang [28].

ATCo needs to be informed. Moreover, potential resolutions need to be generated. In the case of systems with advisory conflict resolution (CR), the generated, potential resolutions need to be presented to the ATCo. In the case of a fully automated CR, the system should generate potential resolutions and then among them, choose one to be implemented.

1.9.1 Desirable attributes that an automated CR system should demonstrate

Apart from safety and efficency, discussed earlier, an essential property that a CD&R system must demonstrate, for evident reasons, is resilience. By resilience here we mean ability of the system to sustain functionalities under both expected and unexpected conditions [29,30]. These properties (safety, efficiency, and resillience), can be translated to several attributes which we can ascribe to

such systems.
Firstly, being in a competitive environment, the airlines will strongly prefer to keep their preferences private. As argued in [31], efficient solution in these circumstances can be achieved through a decentralized system, where all involved aircraft can take decisions collectively, while maintaining some private information.
Secondly, the ability to provide a set of possible resolutions instead of a unique one can contribute to the resilience of the system. As an illustrative example, in a scenario where an aircraft fails to perform the resolution maneuver on time, or with the exact spatial parameters, it is given the chance to perform an alternative resolution maneuver.
Lastly, the ability to consider interdependencies with the surrounding traffic contributes to the safety and efficiency of the system, by preventing the occurrence of new potential conflicts, during the treated time window. Clearly, a procedure designed to identify the relevant surrounding traffic needs to be complete, i.e. all the relevant members need to be identified[20]. Radanovic et al. [32] address the issue. They introduce the concept of aerial ecosystem, being the set of aircraft that are relevant to the conflict resolution. Nonetheless, the actual procedure they propose is not complete, i.e. does not guarantee that all relevant members will be identified[21]. Moreover, they do not formalize the concept of the aerial ecosystem.

1.10 Scope of this Dissertation

The focus of this work lies within the traffic of manned aircraft. As mentioned before, during the tactical face of operations, ATCos are responsible for CD&R. The concepts and models we propose are meant to serve as part of a CD&R advisory system, that could help ATCos to resolve potential conflicts which arise during the en-route flying phase and involve airlines in the generation of possible alternatives. However, the cognitive functions that emerge as result of the application of the proposed methodologies, are not identified as part of this work. Moreover, we are covering en-route traffic and not traffic within terminal maneuvering areas (i.e. areas around airports, where the structure of the airspace is more rigid).
The working hypotheses of this thesis are summarized below:

- The ATCo is responsible to take the final decision regarding the CR process. Agents that represent aircraft can only suggest resolution regions. Nevertheless, the functionalities of the agents can be extended to make them capable of taking responsibility of the CR decision making process in fully automated environments, such as Airbus UTM [33].

[20]Formal definition of completeness is provided in Section 4.4.
[21]More details on the used procedure are given in Section 2.1.1.

- All conflicts are pairwise, i.e. there are no multithreads. However, cases when several pairwise conflicts coexist in time with tight spatial bounds are treated.
- The proposed framework does not consider overtakings, since for them there are already well-accepted procedures.
- False positive conflicts are pre-filtered.
- The used trajectory predictor (TP) is ideal and predicts trajectories in a deterministic manner. However, the framework can be adapted to work with a different TP that is functional in environments that consider uncertainties (e.g. wind uncertainties).
- No prohibited flying zones are present.
- Each aircraft behaves as a point-mass that follows a piecewise linear trajectory, with piecewise constant velocity in a 3D Euclidean space.
- No communication issues can arise. Moreover, the communication between agents is instantaneous. Nevertheless, the proposed protocols can be adapted to work under more realistic communication scenarios.
- The agents that represent the involved aircraft are always willing and able to initiate a negotiation process.
- The agents representing the aircraft are given decision making autonomy during the automatic negotiation process.

These said, the provided ideas can serve as a basis for the development of a system that is capable to perform fully automated CD&R. Moreover, the models can be adapted and investigated within traffic of unmanned aircraft, too. Such an adaptation would require, principally, a more careful consideration of the modeled flying dynamics of the aircraft and the type of services available.

1.11 Objectives of this Dissertation

The main research goal of this dissertation is to *advance the state of the art in automatic air traffic CR at tactical level.*

The topic of automatic air traffic CR, as part of the broader CD&R topic, has been heavily investigated during the last three decades. Nonetheless, several issues are not treated in the current literature. We present five of them. The first three are essential in order to reach a mature state, closer to practical applications for any CD&R solver, or automatic advisory system that are sought to be used in high density scenarios. The forth one encloses the importance of involving airlines in order to achieve efficiency. The last can contribute to the resilience of the system and also becomes important in the context of decentralized CR. In details,

- **Is it possible to provide potential resolutions which exhibit some level of resilience?**
  Literature which treats automatic CR, or generation of CR advisory resolutions, focuses on providing unique resolutions to a given conflict. More specifically, given a set of en-route aircraft, some of which are involved in a potential conflict, the currently proposed solvers provide (at most) one new, deviated trajectory per each aircraft. If these trajectories are followed, the conflict will be avoided. This implies that situations where at least one of the involved aircraft does not perform the exact issued maneuver at the exact determined time can raise safety issues. These issues include causing new conflicts, and not avoiding the initial one.

- **In case it is possible to provide some resilience, can we quantify its levels?**
  Assuming that we are able to provide a family of resolutions instead of unique ones, it is necessary to compare different families of deviated trajectories that resolve a given conflict. A metric that captures their level of resilience is required.

- **Can we achieve a complete surrounding traffic identification and improve its computational efficiency?**
  The completeness of the relevant surrounding traffic identification is vital to guarantee the desired levels of safety. Moreover, the optimization problem we are trying to tackle is of combinatorial nature. This means that the size of the solution space increases in a very high rate as the number of the involved aircraft raises. Therefore, a methodology that can guarantee to involve only a minimal number of the aircraft can bring considerable computational benefits.

- **Can we involve, through a realistic approach, the airlines in the CR decision making in order to improve efficiency, while maintaining safety?**
  In order to improve efficiency of the provided resolutions, all stakeholders, including the airlines, could be involved in the decision making process. This would raise several issues.
  In most of the proposed mechanisms, involved aircraft should declare their costs and/or their strategies. More often than not, the aircraft that cruise airspace belong to different, competing companies. This makes it unrealistic to expect that the airlines will share with each other their cost functions.
  Literature proposes automated negotiation mechanisms as a paradigm that resolve the "cost-declaration" issue. However, in the forms that the proposed mechanisms are constructed, they force involved agents to reach an agreement even in scenarios when their cost would be unacceptable, which does not appeal as realistic.

- **Is it possible to identify on time the latest possible, feasible resolution that would avoid the expected loss of separation?**

The resolution mechanism we propose is an automatic negotiation process between the involved parties. Given that the negotiations will happen in real time, the time during which the involved entities can negotiate, while not jeopardizing safety, needs to be known. Moreover, this information can allow parties to choose their negotiation strategies and the ATCo to have clearer picture of how the process is evolving.

We address these challenges through the following objectives:

- **Provide resolutions that demonstrate some resilience**
  We use spatio-temporal regions in order to provide families of resolution to a given scenario, instead of unique solution configurations. This provides resilience to the system.

- **Propose the "bottleneck"[22] as a measure of the regions' level of resilience.** The "bottleneck" method is a mean through which the level of resilience for spatio-temporal regions can be quantified.

- **Provide a definition of completeness of the relevant surrounding traffic identification.**
  In order to define a structure through which complete surrounding traffic identification can be achieved, we formally define completeness in Section 4.4.

- **Provide a formal construct that serves to achieve completeness of relevant surrounding traffic identification**
  We formalize the aerial ecosystem concept, the mechanism that identifies the relevant surrounding traffic.

- **Propose a computationally efficient implementation of the formalized aerial ecosystem concept through which we can achieve surrounding traffic identification completeness**
  We improve aerial ecosystem identification, by making use of analytically described spatio-temporal regions, to generate a double fold benefit:

  - We achieve completeness in the identification of relevant surrounding traffic.
  - We do so in computationally efficient manner, since the use of regions makes unnecessary to check every possible pair of deviation trajectories.

- **Propose a formulation of the CR problem that allows the use of automatic negotiation as the solution process**
  We evaluate, in the context of CD&R, a negotiating framework, developed already within the automatic negotiation research community. Moreover, we evaluate different negotiating behaviors that the involved parties can manifest.

[22] Defined in Section 3.6.

- **Propose a methodology to identify the temporal fences of the delegated aircraft pairwise conflict resolution framework**
  We propose a method to identify the time limits within which feasible resolutions can be provided. This information is used to set the deadline of the automated negotiation procedure. The approach can serve as a baseline for more refined methodologies to be used in future research.

1.12 Dissertation Overview

The remaining of this dissertation is organized as follows. In Chapter 2 we provide a summary of work regarding CD&R, as well as relevant results from automatic negotiation. The core mathematical object of this work are spatio-temporal regions. Chapter 3 presents their intuition and some concrete implementations. After that, in Chapter 4 we provide a formal definition and a concrete implementation of the aerial ecosystem, i.e. the set of relevant aircraft to a CR. In order to be able to deal with cases when several conflicts coexist in time and have tight spatial bounds, the presented aerial ecosystem concept needs to be extended. In Chapter 5 we propose such an extension and form compound aerial ecosystems.

After relevant ecosystem members are identified, the conflict needs to be resolved. Chapter 6 contains an algorithm intended to resolve conflicts, using spatio-temporal regions and maneuvering a single aircraft. In Chapter 7 we propose a negotiation procedure through which configurations of safe spatio-temporal regions are generated in order to assist CR. Moreover, the algorithm from Chapter 6 is used in order to provide a deadline for the negotiation process. Lastly, Chapter 8 contains the concluding remarks and some future work that can be based on the developed ideas.

Chapter 2

State of the Art

This chapter is divided into two sections. In section 2.1 we summarize results related to the CD&R state of the art, while in section 2.2 we summarize some relevant results about automatic negotiation.

2.1 CD&R Methodologies

There are three issues we cover with respect to the CD&R methodologies. Firstly, we provide an overview of the few results regarding the identification of relevant members. Secondly, we provide an overview of the methodologies used in literature to tackle CD&R and how they stand with respect to safety, efficiency and the three attributes discussed earlier, i.e. resilience, the ability to generate more than one resolving configurations, and the ability to consider interdependencies with surrounding traffic. We finalize the section by providing a summary of various taxonomies that have appeared in literature.

2.1.1 Identification of Relevant Surrounding Traffic

To the best of our knowledge, all works relevant to CD&R, either omit the process of identifying the relevant surrounding traffic, or perform it based on the simple geometric criterion described in the paragraph that follows. Such a course of actions may lead to generation of resolutions that induce new conflicts in the airspace [34].

Once a potential conflict is identified, a large spatial window, that contain the two conflict aircraft, is constructed. All aircraft that are found within this window, during a specified time instance or interval[1], are considered relevant to the resolution. Fig. 2.1 illustrates the idea in two spatial dimensions. There,

[1]Some works construct the windows at the time instance the conflict is detected. Some others, in the context of free flight, where aircraft need to decide over their directions periodically, the windows are constructed at each treated time stamp. Lastly, some consider a time interval, i.e. they consider as relevant traffic all aircraft that pass through the specified volume at some time during the chosen time interval.

the location of the two conflict aircraft, AC_1 and AC_2, indicated also by the red circles, define the location of the filtering window. The used windows can come in different shapes, the preferred ones being rectangles or circles in 2D, and cuboids, cylinders, or spheres in 3D.

This approach raises two main issues. Firstly, it is not complete. There might

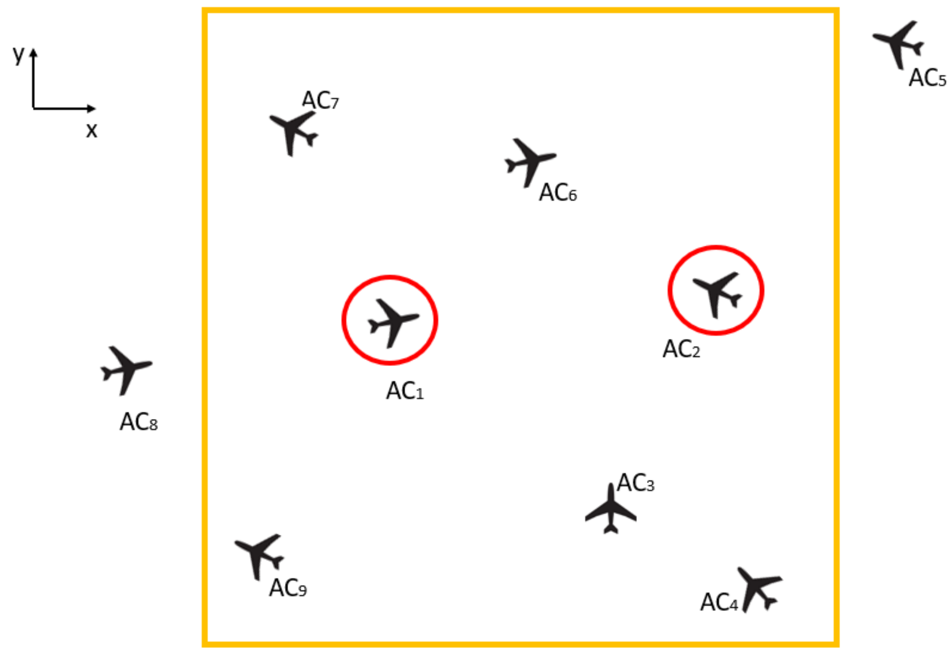


Figure 2.1: Basic geometric identification of relevant surrounding traffic.

be relevant aircraft that will not be identified. For the scenario given in Fig. 2.1, a potential resolution is the one illustrated in Fig. 2.2. Let's assume we resolve the initial conflict by maneuvering AC_2. Further, to avoid an induced conflict between AC_2 and AC_6, we need to also maneuver AC_6. If AC_6 maneuvers as indicated in the figure, we would have a new, induced conflict between AC_6 and AC_5. Since the resolution of the initial conflict induced this conflict, AC_5 is a relevant aircraft to the resolution process between AC_1 and AC_2. However, the used geometric identification methodology did not identify it.

Secondly, if we would consider the actual maneuvers that aircraft can perform, we can conclude that some of the aircraft, indicated as relevant, are actually not. Specifically, AC_7 of the given example cannot be involved in any conflict caused by the resolution of the initial one[2].

[2]Note that the given example is sketchy and has a purpose to give an intuition of the ideas. To be certain about the presented conclusions, the actual dynamics and states of the aircraft need to be considered.

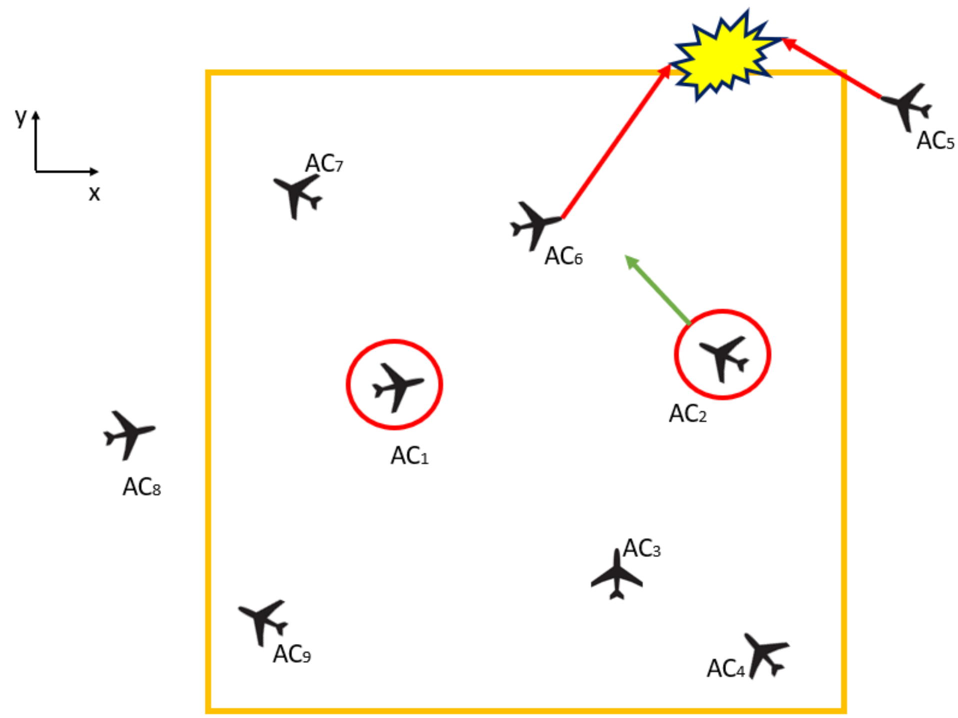


Figure 2.2: A problem might arise using basic geometric identification of relevant surrounding traffic.

Radanovic et al. [32] address the second issue. They first construct a 3D spatial volume around the two conflict aircraft and specify a relevant time interval. Then they consider as potential members all the surrounding traffic aircraft, the trajectories of whom pass through the specified volume, during the specified time interval. They name the set of *potentially* relevant surrounding aircraft "cluster" . In the example illustrated in Fig. 2.3, AC_1 and AC_2 are the two conflict aircraft. The identified cluster members are AC_1, AC_2, AC_3, and AC_4. The black arrows in the figure represent the trajectories that aircraft have to follow. The red, dashed segments illustrate part of trajectories that are in conflict. The orange, dotted, segments illustrate possible trajectories that aircraft could follow.

As a second step, they use the possible deviated trajectories that the cluster aircraft can follow to check if induced conflicts can arise. In this particular scenario, there is a combination of alternative trajectories that if AC_2 and AC_3 would follow, they would be in conflict. Because of this, AC_3 is classified as a relevant aircraft. The set of all relevant aircraft to a given conflict is named "aerial ecosystem". AC_4 does not illustrate a similar behavior. Because of this, it is not considered an ecosystem member. The proposed method, therefore, is able to avoid the consideration of some aircraft that are practically irrelevant. However, the method is not complete. In the given example, AC_5 is discarded

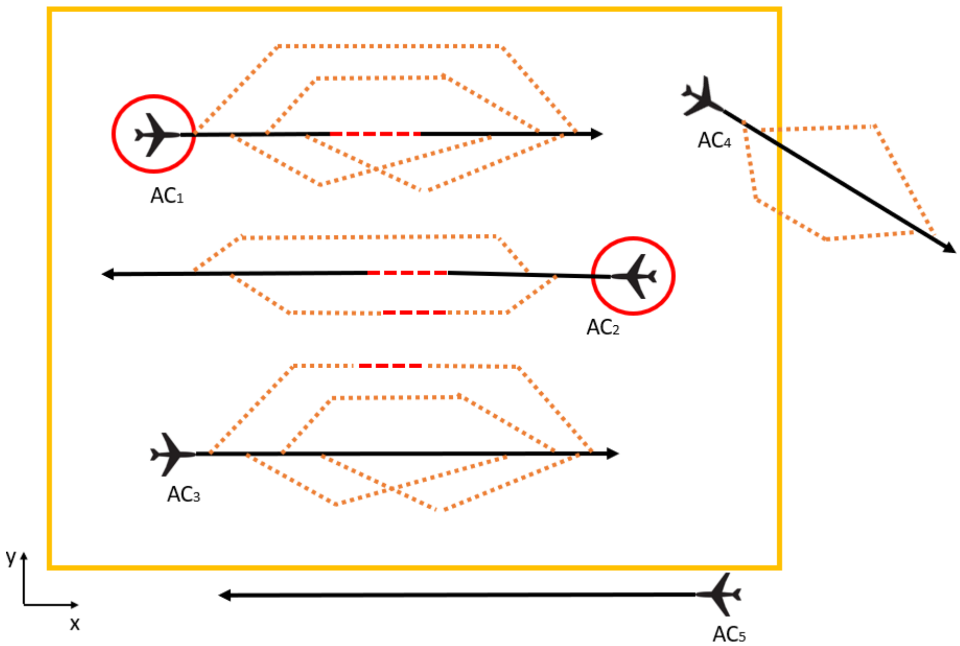


Figure 2.3: Cluster members as of [32].

from the first filter. Although there exist a trajectory that if AC_3 would follow, it would cause a conflict between AC_3 and AC_5, as illustrated in Fig. 2.4.

2.1.2 Conflict Resolution Methodologies

Hu et al. [35] formulate the problem as a global problem, where some energy function is constructed and optimized. A priority is introduced on the involved aircraft and applied to distribute the resolution cost among them. A considerable number of works have modeled the problem as a Mixed-Integer Nonlinear Program (MINP) [36–49] and dispose the proposed priority. Resolutions are sought through reaching a global optimum, in a constrained state-space. Another family of methods seeks to achieve reachable sets [50–52], taking into consideration uncertainties that might arise because of the wind. Visintini et al. [53] make use of Monte Carlo simulations to reach a resolution, while Peyronne et al. [54] propose a genetic algorithm and local optimization in doing so. Koyuncu et al. [55] also formulate the problem as a stochastic optimization problem and utilize the cross-entropy method to reach convergence earlier. Lastly, Volpe Lovato et al. [56] propose a resolution approach via a fuzzy modeling approach and Buongiorno et al. [57] provide resolutions in two-step

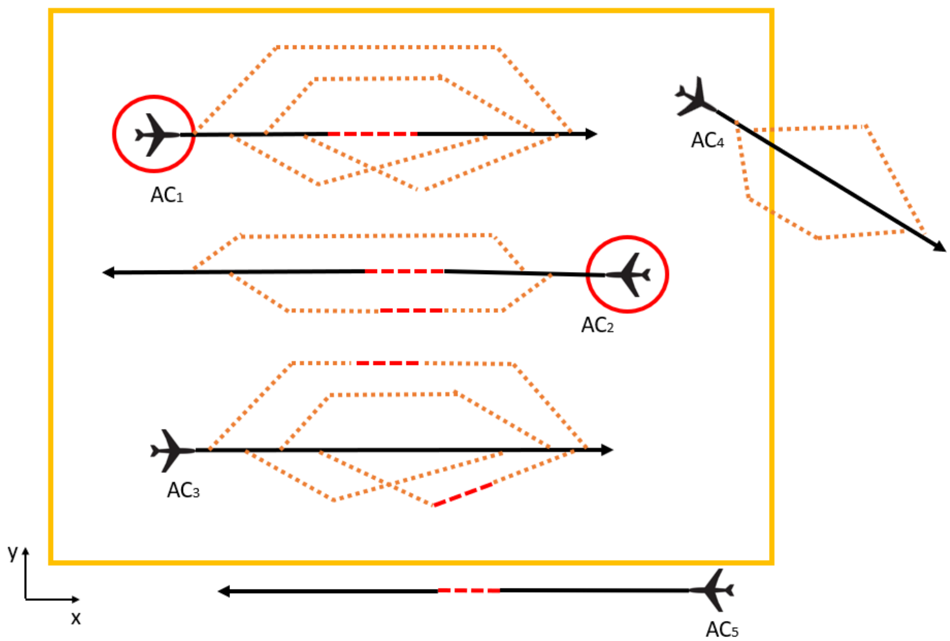


Figure 2.4: The identification method proposed in [32] is not complete.

procedure. First, they seek conflict-free trajectories locally. If this is reached on time, they try to optimize the obtained solutions by trying to introduce direct routing when possible. All the aforementioned approaches, seek solutions in a centralized manner. This implies that they require knowledge of each involved airline preferences in order to attempt pursuing global optima. Moreover, they provide single resolution configurations of the system. Two European funded projects, PHARE [58], and 4DCo-GC [59] make use of spatio-temporal regions to provide families of resolutions. However, they also introduce a centralized decision making mechanism.
Spatio-temporal regions are also used by Hao et al. [60]. There, after associating some probabilistic distributions to the constructed regions, the authors define potential conflicts in a probabilistic manner. This is taken further in [61], where first the probabilistic spatio-temporal regions are identified and discretized. Next, through an Ant Colony Optimization algorithm [62], conflict-free trajectories are constructed using the non-conflict portions of the spatio-temporal regions. This approach is decentralized, can consider surrounding traffic, and it is capable of providing families of resolutions[3]. Nonetheless, the outcome is not Pareto optimal, i.e. not efficient. This occurs because the overlapping, conflict portions of the regions, which are the ones closer to the original trajectories,

[3]Even though the final outcome is made up of trajectories, these trajectories are chosen within the pre-identified conflict-free spatio-temporal regions.

are not permitted to be used. As a result, all involved aircraft are forced to maneuver further from their original trajectories than it is necessary. The use of an automatic negotiation process averts such an outcome. Involved aircraft negotiate over the common conflict part of their regions, with the purpose of dispensing it among them. Thus, a Pareto optimal space-time allocation can be achieved.

Some studies are based on the Voltage Potential methodology [63–66]. The key idea is that, in a pairwise conflict, aircraft are treated as a charged particles of the same sign. Then resolution are constructed by applying an adapted version of Coulomb's law. There are three main issues with this approach. Firstly, the constructed trajectories are not guaranteed to be flyable. Secondly, even they are flyable, it is not guaranteed to be optimal in any sense. Thirdly, there are difficulties in scaling the method in cases with more than two aircraft.

Another wave of approaches treat the system as multi-agent system (MAS) and aspire to identify solutions. In [67–69] authors introduce an unrealistic altruistic behavior in their agents, by adapting the satisficing solution concept [70]. In addition to this, they introduce a hierarchy over the involved aircraft. However, to make such a hierarchy fair, the declaration of the business models of each participant would be necessary. Moreover, provided resolutions are unique. Breil et al. [71] on the other hand, let the aircraft to coordinate through information that they exchange through messages and local, individual decisions they take concerning their velocity module. Again, unique resolutions are provided.

2.1.3 Taxonomies & Surveys of CD&R Methodologies

There are several papers that summarize approaches proposed in CD&R and propose some taxonomies. Kuchar and Yang [28] presents 68 early works on the subject and proposes a taxonomy based on the modeling approaches followed. In a later suvey, Bilimoria [72] epitomizes more recent works and proposes a taxonomy based on the allocation of the separation assurance functions in terms of ground/air and human/automation axes. Lastly, Jenie et al. [73] propose a taxonomy of approaches in an integrated airspace.

A taxonomy based on the modeling approaches of the CD&R system

Kuchar and Yang [28] categorize works based on the various modeling approaches employed by different authors. The used criteria are the way states are propagated, the dimensions of the used states, the provision of explicit conflict detection capabilities, the approach to provide a conflict resolution, the possible resolution maneuvers that each work uses, and the ability to consider multiple conflicts, or not. Among them, we will present some more details regarding the criteria that concern conflict resolution.

The first of them is the way state propagation is modeled. Three different methods that states are propagated are identified. Nominal state propagation projects the current state into the future through a single trajectory, without considering possible uncertainties. The worst-case method assumes no knowledge of the future intentions of the aircraft and therefore a range of potential future states is used as opposed to the unique one used by the first method. Finally, the probabilistic method considers potential trajectory variations in two possible manners. It either adds some error to the state estimations, or it imposes a probability distribution over the set of possible future trajectories.

The second criterion is based on the used state dimensions. Three possibilities are also spotted here. Solution can be sough on horizontal plane only, they can be sough in vertical plane, or on both horizontal and vertical planes.

Thirdly, the approaches used during the CR phase are classified. Predescribed CR, optimized CR, CR based on force fields, manual CR, and no CR are the five identified categories. In predescribed CR resolution maneuvers for different identified scenarios are decided during the design of the system. Their main benefit is that they can provide a resolution in a very short time horizon. However, they tend to be inefficient. In a variety of scenarios they can issue maneuvers more aggressive than necessary. Moreover, they can raise safety issues. Certain scenarios might not be predicted during the design process and therefore it is impossible to provide resolutions for them. Optimization-based CR has as goal to provide resolutions which are efficient under some certain metrics. These can include consideration of economical costs, fuel consumption, delays, environmental costs, etc. Force field approach treats aircraft as charged particles and use equations based on electrostatic principles to generate resolutions. The group that provides manual CR let the ATCo provide resolutions. The last group of works are the works which do not aim to provide CR.

A forth criterion is based on the type of resolution maneuvers that the proposed CD&R provides. Three simple types of maneuvers are specified, heading, level, and speed change. A CD&R can be designed to provide some or all of them independently, or a combination of several ones.

Lastly, a CD&R can be classified based on its ability to consider several conflicts at once, or only a single conflict at a time. In the case of several conflicts, these conflicts can occur independently, in a nearby area, or one can be induced by the resolution of another.

An extra criterion, not used in the referred work, is the information that the solver has regarding the trajectory intent of the involved aircraft[4]. In the case of solvers based on multi-agent systems, this translates to the information that each agent has about the rest of the aircraft's trajectory intent. The provision of this information can determine if a proposed method can work under the free-flight concept, the TBO concept, or both.

A Taxonomy Based on the Locus of the System and the Nature of the Decision Maker

A bit more than a decade later, Bilimoria [72] proposes a new taxonomy for CD&R and classifies more recent works based on their proposed locus of control

[4]While the first criterion of Kuchar and Yang concerns the future state estimation, it does not determine if this estimation is based on exchanged information regarding the intent of the other aircraft, or predictive models that the solver might use.

and their level of automation.
With regard to the locus of control, three classes are defined. Ground-based Control is performed on the ground, by the ANSP[5]. The conflicts are detected and resolved in the ground. Resolutions are then sent to the cockpit crew for execution. On the other hand, in systems with Airborne Control full responsibility for the CD&R is delegated to the cockpit crew. Lastly, a mixed approach is also possible. The control can be shared between the ground and air. There are two ways through which this approach can be implemented. One way involves the delegation of some (or all) of the CD&R related processes to the cockpit crew over a limited amount of time. The other way involves scenarios where in the same airspace some aircraft are under ground-based control and some others under air-based control.
Three levels of automation are further defined, low, moderate, and high. Low automation include systems as the current one. Present CD&R is performed by the human ATCOs. Currently used tools only provide elaborated, relevant information, but do not interfere directly in the decision making. A moderate level of automation includes more decision support tools. In this context, some advisory resolutions can be provided to the ATCo. However, the human ATCo is still responsible for the CR. In a scenario with a high level of automation, most (if not all) the CD&R related processes are performed in an automatic manner. The human role in such systems has a supervising nature.

A Taxonomy Proposed to Work in an Integrated Airspace

Jenie et al. [73] propose a taxonomy of CD&R for manned aircraft, which can be also adapted in the context of Unmanned Aerial Vehicles. This results in a unique taxonomy for all vehicles flying in an integrated airspace. The surveillance type, coordination type, and the type of the issued maneuvers are the three used criteria. Note, however that, because of the time when it was published, this taxonomy does not consider two important works related to Unmanned Flying Systems, specifically the work done within U-space [74] and Specific Operations Risk Assessment (SORA) [75].
Three types of aircraft surveillance are noted, centralize-dependent surveillance, distributed-dependent surveillance, and independent surveillance. A system with centralize-dependent surveillance obtains data from a single station in order to perform its CD&R. A distributed-dependent-surveillance system requires all involved aircraft to broadcast their data. The last approach required no communication, or information sharing. Each aircraft surveils the traffic using its own sensors and exchanges no information with the other vehicles.
The level of coordination between the involved parties is also considered. The three levels of coordination that are differentiated are explicit coordination, implicit coordination, and absence of coordination. The coordination is said to be explicit in case real-time communication is used among the involved parties. In case a set of predefined, permitted rules are used, then the type of coordination

[5] In the current system, at tactical level, by the ATCos.

is said to be implicit. Finally, if no communication exists, and no predefined rules neither, we are in the conditions of lack of coordination.
The types of maneuvers encode the amount of the change that the maneuver causes in the initial trajectory. Strategic maneuvers cause significant change to the flight path. Tactical maneuvers change a small part of the flight path. Lastly, escape maneuvers are meant to avoid collision.

2.2 Automated Negotiation

According to Lawler and Pritt [76], "negotiation is a process by which a joint decision is made by 2 or more parties. The parties first verbalize contradictory demands and then move towards agreement by a process of concession making or search for new alternatives". Such a process is performed routinely in various aspects of human interactions. However, various works have shown that negotiation is a difficult task for humans. Two factors that worsen our performance are our bounded rationality and the involvement of emotions in our decision making. In certain scenarios the solution space of the problem we are trying to solve is too big. In these scenarios, our bounded rationality makes it impossible to explore the whole space and reason to find a good outcome. On the other hand, our emotions often lead us to take decisions which are not rational. We refer here to "rationality" in the classical game theoretic sense. Albeit there are works that try to demonstrate benefits of "irrational" decision making, or some misconceptions about it [77–79], we retain our focus within classical game theory. This has lead research to investigate the possibility of automating negotiation. Succesful applications of automated negotation can be found in a wide range of fields including, but not being limited to, e-commerce [80], politics [81], cloud-computing [82], resource allocation [83].
At an abstract level, a negotiation process involves several parties, which have interests that most commonly do not agree with each other. These parties interact between them through a set of rules, known as the negotiation protocol. A negotiation protocol determines how do the involved parties interact, how do they exchange information, what are the valid actions that a party can take, when does the negotiation ends, and how is the final decision taken. A classic example of a protocol is the alternating offers protocol [84]. Through this protocol, a pair of parties can interact. Party P_1 starts the process by offering a solution to the other party, P_2. P_2 can accept the proposal or reject it. If the later is the case, then P_2 should propose a counter-offer. In the original form of the protocol, there was no time limitation, i.e. if an agreement is not reached, the process continues endlessly. In another form, the protocol has a deadline [85]. Such deadline can be expressed in time, or number of negotiation rounds[6]. If no agreement is reached at the end of it, the process terminates unsuccessfully. In case an agreement is reached before the unsuccessful termination, then the process is finalized with success. Fershtman and Seidman [86] modify the protocol further by introducing a lottery on each round to choose

[6] A negotiation round is a single exchange of offers between the two parties.

which party will propose a new offer. Aydogan et al. [87] propose two versions of the protocol that be used in cases when more than two parties need to negotiate.

There are several works that extend the alternating offer protocol to cases when more than two parties negotiate. Klein et al. [88] proposes a version where each party is negotiating with all other parties through simultaneous bilateral negotiation processes. Several other works [89–91] propose the use of a mediator party to coordinate the negotiation process. Lastly, DeJonge and Sierra [92], as well as Aydogan et al. [87] propose several variants for negotiation between more than two parties without the need of a mediator.

Regardless of the policy, each party should have a negotiation strategy. Through this strategy, the party is able to evaluate bids that receives from the other parties, as well as generate new bids to offer to the rest of the parties. During both these processes, the party must consider the preferences of the user it represents. Fig. 2.5 provides a schematic representation of a negotiation party. As we see, the party generates bids through its bid generator module and offer them to the other parties. As soon as a received offer arrives, the party, through its bid decider module decides if it will accept the offer, or will reject it and generate a new one. Arguably, the most influential work on the negotiating party's strategy was done by Faratin et al. [93]. They present several families of agents' "negotation tactics", among which, the family of time dependent negotiation tactics. Given that each party chooses an initial offer and her reservation value[7], through a time dependent behavior it is suggested to offer at the beginning of the negotiation the initial value and at the end of it the reservation value. Furthermore, at each time step, through a function that maps time to a suggested cost, the most adequate alternative to be offered is chosen. In systems where a party tries to minimize costs, such a function would be monotonically increasing[8]. Beyond this, several other models have been presented in the Automated Negotiating Agents Competition (ANAC), an annual competition used by the automated negotiation research community to benchmark and evaluate its work [94].

2.2.1 Automated Negotiation in the Context of CD&R

A negotiation procedure in the context of conflict resolution is introduced by Wollkind et al. [95] and Pritchett and Genton [31]. There, in each round involved aircraft are asked to propose more costly maneuvers. The key difference between the two is that Pritchett and Genton allow different aircraft to have different cost functions, while Wollkind et al. assumes the same cost function for all participants. The three issues that such an approach raises are the uniqueness of the provided resolutions, the fact that they overlook relevant surrounding

[7]The reservation value of a negotiation party, is the offer of the highest individual cost that the party is willing to pay to reach an agreement.

[8]This in case the utility functions represent a cost that we are trying to minimize. In case the utility function represents a profit, then the behavior function should be monotonically decreasing

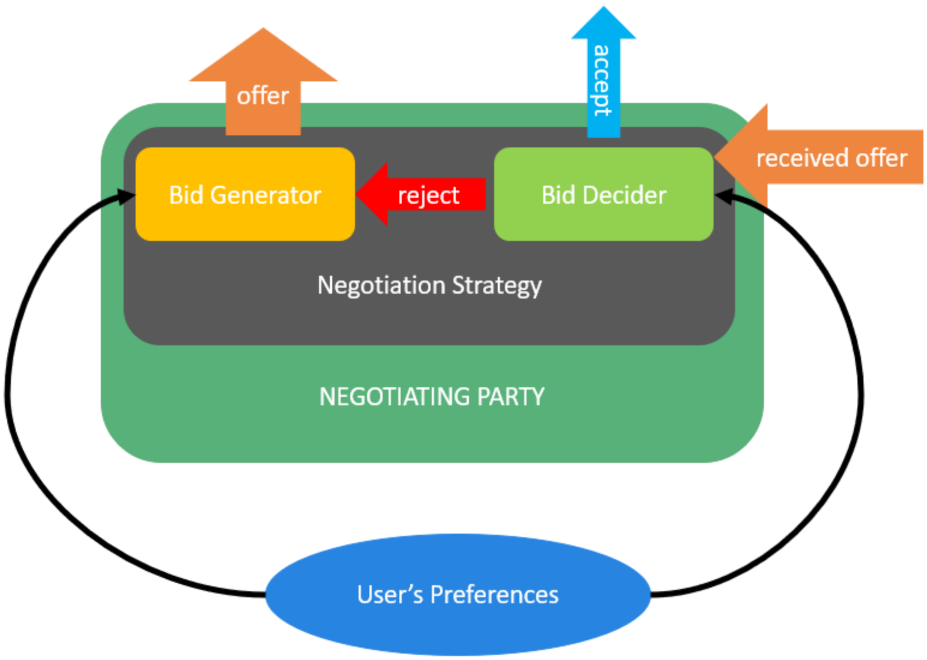


Figure 2.5: A schematic representation of a Negotiation Party.

traffic, as well as they do not identify the deadline of the negotiation. By the way the mechanism are designed, they converge in finite time. However, this finite time might exceed the latest possible time instance at which a resolution can be provided.

Chapter 3

Spatio-Temporal Regions

To tackle scalability and resilience, this work relies on spatio-temporal regions, instead of individual trajectories. We will describe in this chapter how spatio-temporal regions based on different types of maneuvers can be constructed and formalize what it means for two regions to be in conflict (informally, two spatio-temporal regions are in conflict if they contain a pair of points the distance between which is less than the minimum allowed separation). We construct two types of regions. The first one is based on a change of heading and velocity module and second one is based on change of the heading only. The main advantage of the first method is that it induces no delays in the system. On the other hand, the main advantage of heading-based regions is that they cover a wider range of maneuvers and can tackle more conflict geometries. The chapter starts by first formalizing the trajectory model we use and quantifying an en route conflict.

3.1 Discretized Trajectory Model

We employ a widely used technique to model the aircraft dynamics, which is used in almost all reviewed works in CD&R [36–52, 54, 55, 57, 60, 63–69, 71]. The trajectory of the flight is modeled as a series of 4D (space-time) waypoints. The aircraft is treated as a point mass in a 3D Euclidean space, evolving over time. We obtain its x and y coordinates by applying the stereographic projection [96] on the its latitude and longitude. The z coordinate represents the aircraft's altitude. During the flight, the involved aircraft are assumed to have piece-wise constant velocity between two consecutive waypoints. Moreover, planar maneuverability constraints are modeled by the impose of a maximum angle by which an aircraft can deviate. Constraints are also used on the maximum velocity that an aircraft can reach. We assume an ideal TP that predicts accurately the position of aircraft at each time instance.
Given the above, the flight state variables of the aircraft is specified as (x, y, z, v_x, v_y, v_z), where (x, y, z) are its coordinates and (v_x, v_y, v_z) its velocity compo-

nents.

3.2 Quantifying a Conflict

According to current specifications, each pair of en route aircraft needs to maintain a minimum horizontal separation and a minimum vertical one [16]. The exact quantities depend on the location of the aircraft and their velocities.
Formally, given that an aircraft AC at a given time instance t, can be described by its position $\vec{p}(t) = [\vec{p_h}(t), z(t)] = [x(t), y(t), z(t)]$, a conflict between AC_1 and AC_2 described respectively by $\vec{p_1}(t)$ and $\vec{p_2}(t)$ can be defined as:

$$\begin{cases} d_H(\vec{p_{h1}}(t), \vec{p_{h2}}(t)) < h(\vec{p_1}(t), \vec{p_2}(t), \dot{p_1}(t), \dot{p_2}(t)) \\ d_V(z_1(t), z_2(t)) < v(\vec{p_1}(t), \vec{p_2}(t), \dot{p_1}(t), \dot{p_2}(t)) \end{cases} \tag{3.1}$$

where $d_H(v_1, v_2)$ (and $d_V(v_1, v_2)$) is a distance function[1] between vectors (and scalars) v_1 and v_2, $h(p_1, p_2, \dot{p_1}, \dot{p_2})$ is the minimum horizontal separation required between the two aircraft, as a function of their position and velocities and $v(p_1, p_2, \dot{p_1}, \dot{p_2})$ is the minimum vertical separation required between the two aircraft, as a function of their position and velocities.
A common simplification of the above conditions, used in CD&R development is assuming that the minimum separation distances are constant, i.e.

$$\begin{cases} d_H(\vec{p_{h1}}(t), \vec{p_{h2}}(t)) < H \\ d_V(z_1(t), z_2(t)) < V \end{cases} \tag{3.2}$$

where H, V are two constants. In practice, the most common values for these constants are $H = 5$ Nautical Miles (NM) and $V = 1000$ feet (ft).

3.3 Assigning Continuous Space-Time Regions to En Route Aircraft

The core idea of continuous space-time regions lies in the observation that instead of trying to assign a single trajectory to each aircraft that must maneuver to solve a detected conflict, a space-time region can be given to each one of them.
Mathematically, classical approaches assign to each aircraft a function describing their motion:

$$\begin{cases} x = x(t) \\ y = y(t) \\ z = z(t) \end{cases} \tag{3.3}$$

[1] Euclidean distance is the distance function widely employed.

Assigning a region instead could be expressed as:

$$[x(t), y(t), z(t)] \in V(t) \tag{3.4}$$

where $V(t)$ is a dynamic volume, evolving over time.
Fig. 3.1 illustrates a safe space-time region assigned to an aircraft in a world

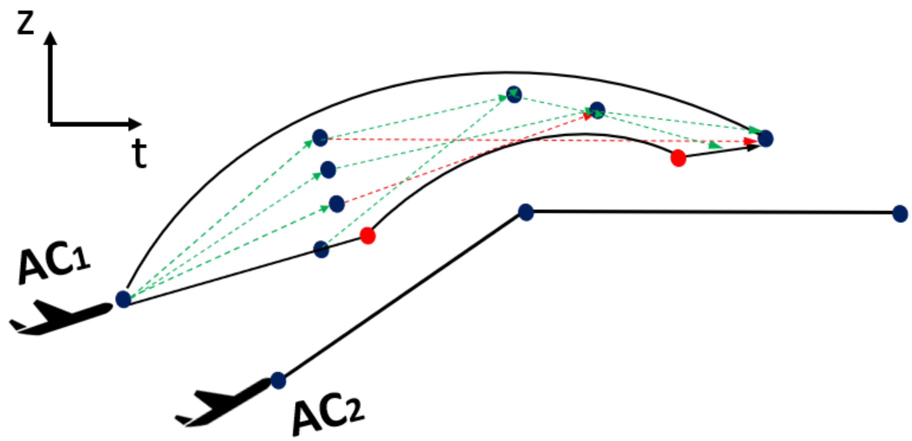


Figure 3.1: Assigned safe region for AC_1 and examples of various legs it can construct (green segments), or not (red segments).

with a single spatial dimension (z coordinate) and time. The black continuous curves represent the border of AC_1 safe region (i.e. a guaranteed conflict-free area), the green dashed lines represent feasible legs that AC_1 can fly, the red dashed lines represent legs which might cause a loss of separation, i.e. a conflict and the black dots are feasible, conflict-free waypoints for AC_1.

3.3.1 Resilience Advantage of Spatio-Temporal Regions Compared to Unique Trajectories

One of the main advantages that providing spatio-temporal regions instead of unique trajectories brings in the context of CD&R is resilience. We can talk about resilience related to own aircraft and factors related to surrounding traffic aircraft.
As illustrated in Fig. 3.2, AC_1 is capable to choose among various deviated trajectories[2] that resolve the conflict with AC_2. As an example, assume we are in a situation when AC_1 has decided to follow the deviated leg that starts at the time instance t_1 of the figure, but for some reason, when t_1 comes the maneuver is not performed, or the aircraft is not at that exact spatial point.

[2]Mathematically speaking, infinitely many

Reasons can vary from the reaction time of the pilot to weather uncertainties, or uncertainties of the tracking. A potential alternative is the deviated leg that starts at t_2.

Uncertainties can be related to AC_2 also, as well to other surrounding traffic

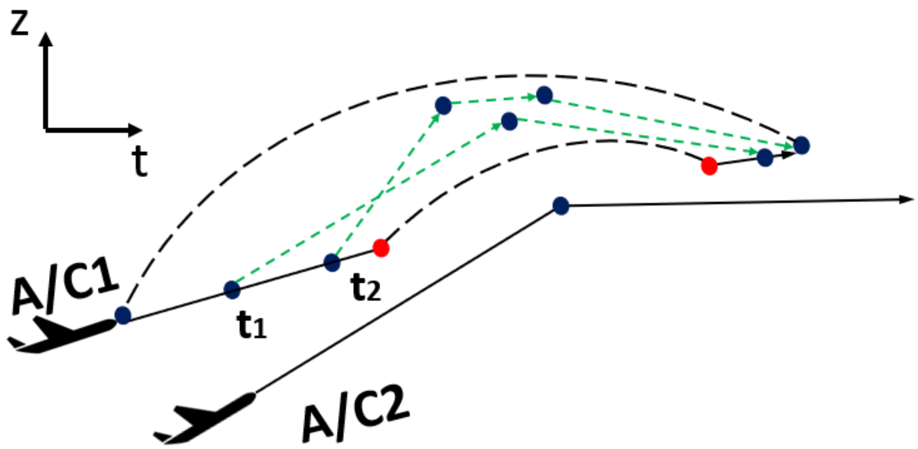


Figure 3.2: Two deviated trajectories, taken at different time instances that solve the conflict.

aircraft. As it will be illustrated in Chapter 6, in case the state of AC_2 changes in an unexpected way, AC_1 can use the already constructed spatio-temporal region to adapt to this change and provide an alternative resolution without the need to consider other external factors.

3.4 Continuous Space-Time Regions Implementation That Avoids Delays Generation

Using the above-mentioned idea, we will construct a family of space-time regions with second order polynomial borders[3]. Our assumptions include constant horizontal velocity and linear horizontal trajectories of the involved aircraft before resolving the conflict. This means that the part of the aircraft's trajectory during the considered time interval is completely described by its position at the beginning of the interval, i.e. the start point, and at the end of the interval, i.e. the final point. Despite these constraints can be quite realistic when applied close to the Closest Point of Approach (CPA), it is well accepted that they could be restrictive for long time horizons. However, the model can be generalized to cases with variable velocities and piece-wise polynomial trajectories.

[3] The choice of second order polynomial borders is justified later in this section

An interesting interpretation of Eq. 3.4 can be done in a coordinate system where the x axis is the direction of the aircraft movement and the y axis is the direction normal to it, as illustrated in Fig. 3.3. In this case an assigned region of the form:

$$\begin{cases} x_l(t) \leq x \leq x_u(t) \\ y = y_c \\ z = z(t) \end{cases} \tag{3.5}$$

can be interpreted as allowing the aircraft to change the module of its velocity in order to avoid the conflict, while not changing its heading[4]. Note that y_c stands for a constant value of the y coordinate.

Eq. 3.5 describes the case when the aircraft can only vary its velocity modu-

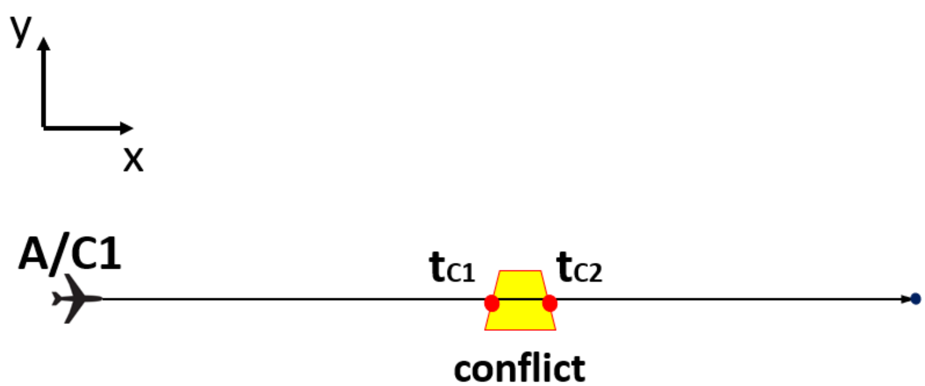


Figure 3.3: The coordinate system is constructed after the direction of the aircraft movement

lus, while maintaining its spatial trajectory. In an enriched scenario where the assigned region has the form of:

$$\begin{cases} x = x(t) \\ y_l(t) \leq y \leq y_u(t) \\ z = z(t) \end{cases} \tag{3.6}$$

the aircraft is given the freedom to change its heading and its velocity module at the same time, while it is forced to maintain its x coordinate. As illustrated in Fig. 3.4, for regions of this form at each time instance an aircraft is given a segment perpendicular to its original trajectory instead of a single point.

What we further want is to have an analytic description of the borders of this space-time region. The outer bound, in order to enhance the method solving capability, should include as much space as possible around the conflict interval.

[4]If the module is changed twice, in certain ways, the final 4D waypoint can be maintained as well.

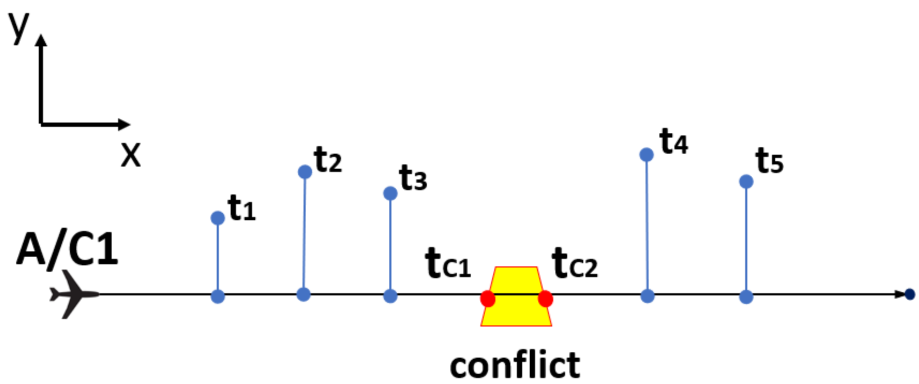


Figure 3.4: At each time instance an aircraft is given a segment perpendicular to its original trajectory

Moreover, to avoid introducing downstream delays, which can lead to potential later conflicts, the end point of the resume maneuver should coincide with a 4D waypoint found in the original trajectory of the aircraft. Its convexity and simplistic analytical description, makes a parabola a suitable choice, as illustrated in Fig. 3.5.

Mathematically the region is described by:

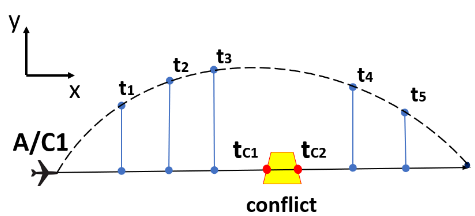


Figure 3.5: A region with a parabolic outer bound. At each time instance a segment perpendicular to its original trajectory is assigned to the aircraft

$$\begin{cases} x = x(t) \\ y_0 \leq y \leq a_{yu}t^2 + b_{yu}t + y_0 \\ z = z(t) \end{cases} \tag{3.7}$$

where a_{yu} is the maximum allowed value of the y component of the acceleration, b_{yu} is the value of the the y component of the initial velocity in the hypothetical scenario that we would follow the parabolic trajectory, and y_0 the value of the initial y coordinate of the aircraft. Note that, even though the border has an acceleration component, we can still construct within the region piece-wise linear trajectories with piece-wise constant velocities.

3.4.1 Conflict between parabolic regions

In this part, we define a conflict between two parabolic regions. Let AC_1 and AC_2 be the two aircraft. Using Eq. 3.7, fixing the origin at start point of AC_1, the x-axis according to AC_1 velocity vector and the y-axis according to the direction we want to have the parabolic extension, the region of AC_1 is:

$$\begin{cases} x = x_1(t) \\ a_{y1l}t^2 + b_{y1l}t + y_{1l} \leq y \leq a_{y1u}t^2 + b_{y1u}t + y_{1u} \\ z = z_1(t) \end{cases} \tag{3.8}$$

The lower bound of the inequation in 3.8 is a generalized version of the lower bound of the inequation in 3.7.
Similarly the region of AC_2 can be expressed as well:

$$\begin{cases} a_{x2l}x_2^2(t) & +b_{x2l}x_2(t) + c_{x2l} \leq x_2 \\ & \leq a_{x2u}x_2^2(t) + b_{x2u}x_2(t) + c_{x2u} \\ a_{y2l}y_2^2(t) & +b_{y2l}y_2(t) + c_{y2l} \leq y_2 \\ & \leq a_{y2u}y_2^2(t) + b_{y2u}y_2(t) + c_{y2u} \\ z_2 = z_2(t) \end{cases} \tag{3.9}$$

Because the direction of movement of AC_2 does not necessarily coincides with the direction of the axes of the coordinate system (which are chosen after the direction of movement of the other aircraft), the upper and lower bounds on both its x and y components have parabolic shapes[5].
As illustrated in Fig. 3.5, a space-time region can be interpreted as a spatial segment changing its length and moving over time, therefore our conflict is a loss of minimum separation between two segments parametrized over time. The distance between two arbitrary segments $[P_{1,1}P_{1,2}]$ and $[P_{2,1}P_{2,2}]$ can be expressed as:

$$d([P_{1,1}P_{1,2}], [P_{2,1}P_{2,2}]) := \min_{i,j \in 1,2} d([P_{i,1}P_{i,2}], P_{3-i,j}) \tag{3.10}$$

which in our case would translate:

$$d([P_{1,1}(t)P_{1,2}(t)],[P_{2,1}(t)P_{2,2}(t)]) := \min_{i,j \in 1,2} d([P_{i,1}(t)P_{i,2}(t)], P_{3-i,j}(t)) \tag{3.11}$$

where $P_{i,j}(t) = v_{i,j} * t + p_{0,i,j}$ are the end points of AC_i's parametrized segment. Changing the coordinate system such that $P_1(t)$ is its origin, y-axis is the direction of $[P_1(t)P_2(t)]$ with $P_2(t)$ in the positive part, the coordinates of $P_1(t)$,

[5] In a coordinate system where x axis would coincide with the direction of movement of AC_2 and y axis with the direction normal to the direction of movement of AC_2, AC_2 equation of region would have the form of Eq. 3.8 and AC_1 equation of region would have the form of Eq. 3.9

$P_2(t)$ and $P_3(t)$ will have a form:

$$\begin{cases} P_1(t) = (0, 0) \\ P_2(t) = (0, \alpha_{2y}t^2 + \beta_{2y}t + \gamma_{2y}) \\ P_3(t) = (\alpha_{3x}t^2 + \beta_{3x}t + \gamma_{3x}, \alpha_{3y}t^2 + \beta_{3y}t + \gamma_{3y}) \end{cases} \tag{3.12}$$

The distance of $P_3(t)$ from $[P_1(t)P_2(t)]$ is therefore given by[6]:

$$||P_2(t)P_3(t)|| \leq H \vee ||P_3(t)|| \leq H \tag{3.13}$$
$$\vee \begin{cases} |\alpha_{3x}t^2 + \beta_{3x}t + \gamma_{3x}| \leq H \\ 0 \leq \alpha_{3y}t^2 + \beta_{3y}t + \gamma_{3y} \leq \alpha_{2y}t^2 + \beta_{2y}t + \gamma_{2y} \end{cases}$$

where H is the minimum planar separation.
Some straightforward mathematical manipulations can transform each of the above inequations to a forth order polynomial inequality, which can be solved analytically [97].
Similarly we can calculate all four distances required in the Definition 3.11.

3.5 Continuous Space-Time Regions Implementation Based on Heading Change

In this section we develop another implementation of regions that include all feasible heading alteration maneuvers for an aircraft. Our assumptions include constant velocity and linear trajectories of the involved aircraft[7].
We consider maneuvers with heading change only. Maneuvers based on altitude, planar velocity module change, or combinations of some of the above, can be treated in a similar manner[8].
Let x_0, y_0, z_0, t_0 be the starting 4D waypoint from where we can consider possible heading alterations. We model the combination of physical limitations with the desired intent of the aircraft by the imposition of a maximal angle of deviation α_{max}. This results in a situation where if the aircraft performs a heading change at t_0, at a given time t, it will be found on the arc bounded by the radius forming an angle of α_{max} with the original trajectory and the radius forming an angle of $-\alpha_{max}$ with the original trajectory. The arc will lie on the circle with center $[x_0, y_0]$ and has a radius $r(t) = ||\vec{v}||(t - t_0)$. Fig. 3.6 depicts the situation.
For construction reasons, we want to divide this family of arcs into two subfamilies, each one of them being bounded, as depicted in Fig. 3.7 and 3.8, by the original trajectory and the limits of the original arcs.
In constructing theses spatio-temporal regions, there are two issues we need to

[6]The closest point of a segment $[P_1P_2]$ from a point P_3 can be P_1, P_2, or an internal point
[7]These constraints are relaxed in the subsection 3.5.2, where piece-wise linear trajectories and piece-wise constant velocities are assumed
[8]We provide the models for the altitude and velocity module cases in the appendix A.

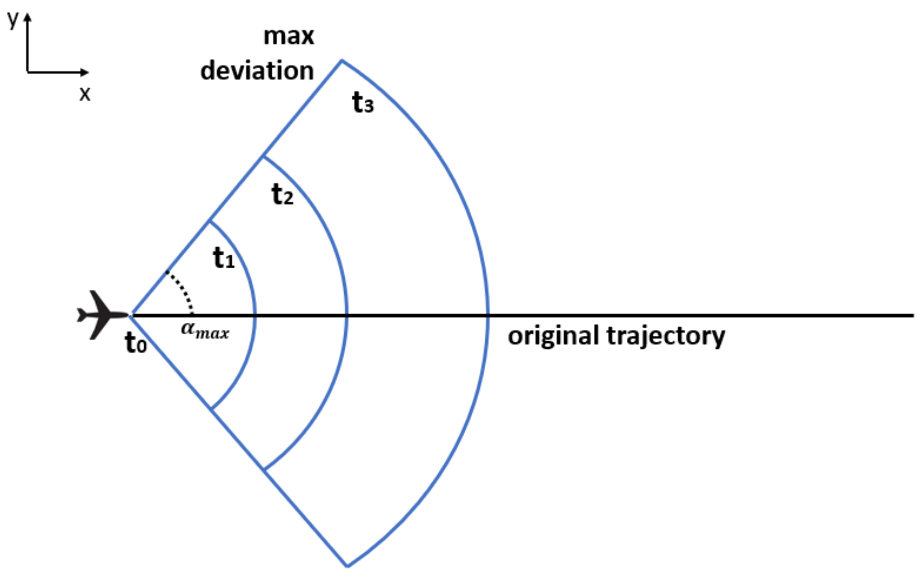


Figure 3.6: Resulting arcs by performing a heading change at t_0.

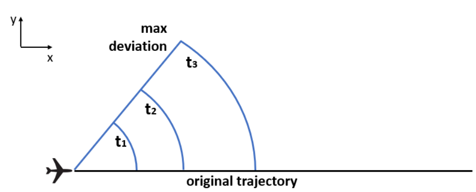


Figure 3.7: Family of upper arcs.

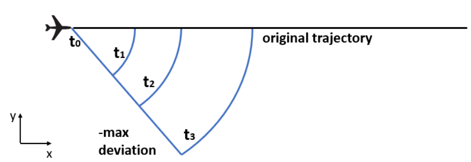


Figure 3.8: Family of lower arcs.

address. The first one is that a change of heading can be performed at various time instances, as shown in Fig. 3.9. The second one is the necessity for a way to return to the original 3D trajectory.

Dealing with the first issue is more straightforward. We can define some linear

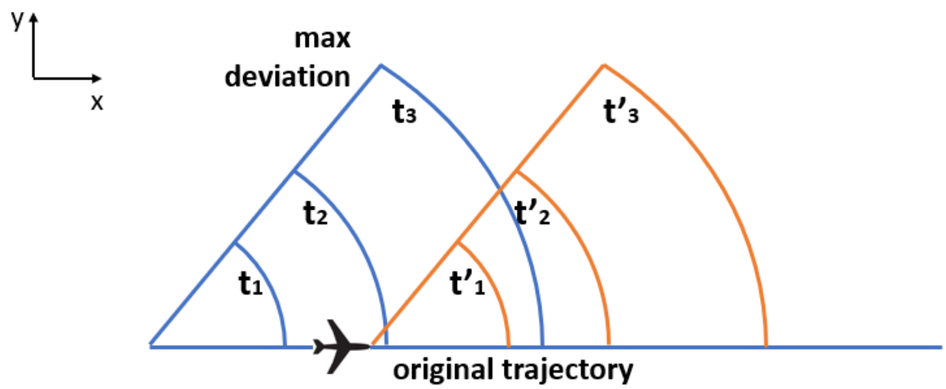


Figure 3.9: A heading change can be performed at various time instances.

bounds[9] as the one depicted in Fig. 3.10. The outer bound can be interpreted as the worst trajectory (in terms of divergence from the original trajectory) that the aircraft can be assigned in the given space-time region.

To deal with the second issue, at each time instance, regions as the one shown

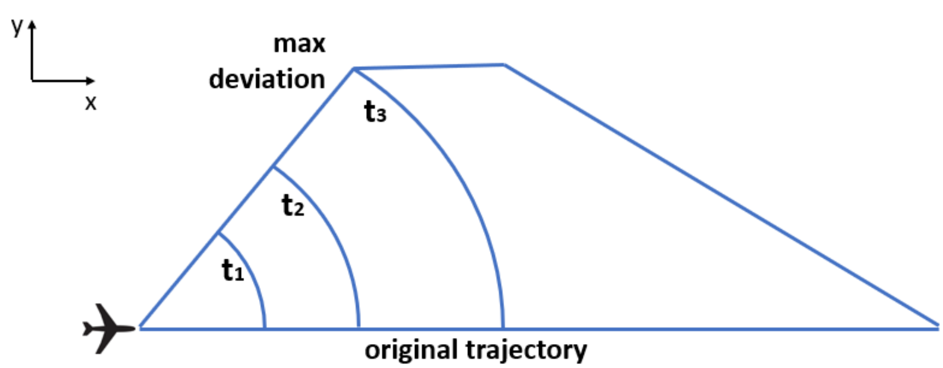


Figure 3.10: Constructed linear bounds.

in Fig. 3.11 need to be considered. The depicted space region is bounded by the arc $\hat{CD}$ and the segments $[BC]$ and $[DB]$ and is assigned to the aircraft at time instance t_i[10]. More formally, we would assert:

[9]In a practical situation bounds are used to describe acceptable delays with respect to the original 4D trajectory. To measure this maximal delay, some global perspective of the system considering the preferences of the airline, the Target Time of Arrival and the Controlled Time of Arrival, and the traffic conditions is required and this goes beyond the scope of this work.

[10]t_i is the time when the aircraft would have reached point C, if it would have followed its original trajectory.

Theorem: *Let the region $R(t_i)$, bounded by $[DB]$, $[BC]$, and $\hat{CD}$, depicted in Fig. 3.11, be the space region assigned to the aircraft at the time instance t_i. Let the aircraft be at time instance $t = t_A : t_A \leq t_i$ at the point A, which lies on its original trajectory. Moreover, let E be an arbitrary point that the aircraft want to reach at $t = t_i$ by maneuvering at $t = t_A$. Then $\angle EAC \leq \angle DAC \implies E \in R(t_i)$.*

where $\angle EAC$ is the small angle formed by the segments EA and AC.
The space-time region, $R(t)$, we want to assign to an aircraft is therefore an

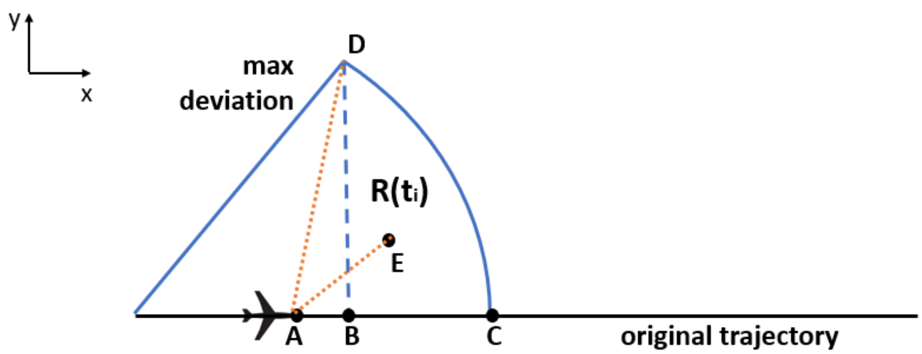


Figure 3.11: A heading change can be performed at various time instances.

evolving surface (bounded by two evolving segments and an evolving arc), which can be divided in three sub-regions, Fig. 3.12. $R_e(t)$ has an arc which moves in the direction defined by the aircraft's initial velocity and is expanding as time evolves, $R_p(t)$ has an arc that only moves in the direction defined by the aircraft's velocity and $R_{sh}(t)$ has an arc that moves and also shrinks as time evolves. Time instances t_1 and t_2 are the instances of change between the regions and defined by the time when the aircraft would have reached points A_1 and A_2 respectively, if it would follow its original trajectory.

3.5.1 Loss of Horizontal Separation between Regions

To define the inter-regional conflict, we propose to approximate the arcs by series of segments. In this way a region $R(t)$ will be approximated by an evolving polynomial $P(t)$.
There are well-known methods in Computational Geometry to find the distance between two fixed polygons [98], however in this section, to avoid time-discretization, we will make use of the fact that the vertices of the polygon evolve in a linear manner. A loss of separation between the evolving polygons can be seen as a loss of separation between pairs of moving segments.
The distance between two arbitrary moving segments $[P_{1,1}(t)P_{1,2}(t)]$ and $[P_{2,1}(t)P_{2,2}(t)]$,

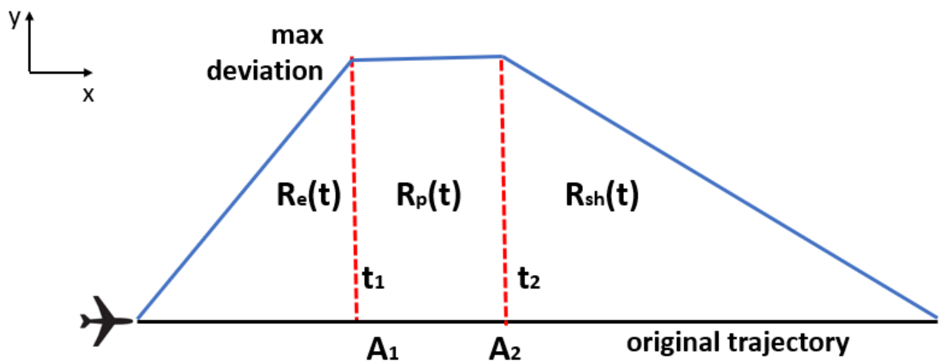


Figure 3.12: The three sub-regions of the defined region.

as pointed out by Eq. 3.11, can be expressed as:

$$d([P_{1,1}(t)P_{1,2}(t)],[P_{2,1}(t)P_{2,2}(t)]) := \min_{i,j\in 1,2} d([P_{i,1}(t)P_{i,2}(t)], P_{3-i,j}(t)) \tag{3.14}$$

where $P_{i,j}(t) = v_{i,j} * t + p_{0,i,j}$ is a vertex of a polygon belonging to AC_i, $v_{i,j}$ its velocity and $p_{0,i,j}$ its initial position.
The closest point of a segment from a point can be one of the segment's end-points, or an inner point of the segment. Let our segment be $[\vec{p_1}(t), \vec{p_2}(t)]$ and the point $\vec{p_3}(t)$, where $\vec{p_i}(t) = \vec{p_{0i}} + t\vec{v_i}$, then the procedure to to check if there is a loss of separation between a moving point and a moving segment is the following:

- Check if there is a loss of separation between the point $\vec{p_3}(t)$ and each of the two end-points.

- Check if there is a loss of separation between $\vec{p_3}(t)$ and an inner point of the segment $[\vec{p_1}(t), \vec{p_2}(t)]$.

- Calculate the conflict interval as the union of the three resulting conflict interval

Loss of separation between two moving points The distance between two points is:

$$d(\vec{p_i}(t), \vec{p_3}(t)) := ||(\vec{p_{0i}} - \vec{p_{03}}) + t(\vec{v_i} - \vec{v_3})||$$

To have a loss of separation we require:

$$d(\vec{p_i}(t), \vec{p_3}(t)) < H$$

where H is the required minimum horizontal separation.
This expression can be easily transformed in a polynomial equation of second order with respect to t and can be solved analytically.

Loss of separation between a moving point and an inner point of a moving segment, when the closest point between the point and the segment is an internal segment point Let $\vec{p_{ij}} := \vec{p_i} - \vec{p_j}$ and $\vec{n}(t) = \vec{p_n} + t\vec{v_n}$ be the normal to the line that includes $[\vec{p_1}(t), \vec{p_2}(t)]$, which means that $\vec{p_n}(t) := [x_{21}(t), y_{12}(t)]$ and $\vec{v_n} := [v_{x21}(t), v_{y12}(t)]$, then the procedure is the following:

- Find the time intervals during which the closest point between the line on which the segment lies and the point is an interior segment point.
  The condition to be satisfied is $sign(\vec{n}(t) \cdot \vec{p_{31}}(t)) \neq sign(\vec{n}(t) \cdot \vec{p_{32}}(t))$[11], which transforms in a pair of second order polynomial inequalities with respect to time and can be solved analytically.

- Find the time intervals during which there's a loss of separation between the line and the point
  The distance between a point $p = (x_0, y_0)$ and a line $l : (a, b, c$ is:

$$d = \frac{|ax_0 + by_0 + c|}{\sqrt{a^2 + b^2}}$$

  which translates in our case to:

$$\frac{|\vec{n}(t) \cdot \vec{p_{31}}(t)|}{||\vec{n}(t)||} \vee \frac{|\vec{n}(t) \cdot \vec{p_{32}}(t)|}{||\vec{n}(t)||}$$

  and can be further transformed in forth order polynomial with respect to time, which can be solved analytically.

- Find their intersections t_1.

- Find the intersections t_2 of t_1 with the interested time interval.

- Find the intersection of t_2 with the time interval during which there is a vertical loss of separation.

3.5.2 Generalization to Piece-wise Linear Trajectories

In this section we present a more general model. We will consider piece-wise linear trajectories with piece-wise constant velocity.
As can be seen in Fig. 3.13, to pass the region from one linear segment of the trajectory to the next one, a rotation must be performed if we want to maintain the inner bound on the original trajectory. Such a rotation would introduce non-linearities in the velocity of the regions for the transition period, which for now, considering piece-wise constant velocities, we want to avoid. There are

[11] Intuitively we are asking the point to be on opposite sides of the lines, perpendicular to our segment and passing each from one of its end-points

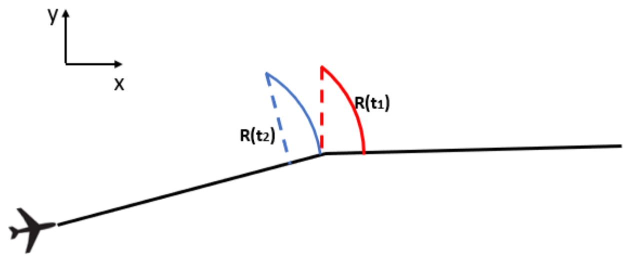


Figure 3.13: The space region before and after the change of the segment.

various ways to get through such a problem, one of which is by constraining the expanding part of the space-time region to happen only during the time interval of one particular segment. As soon as the next segment starts, the parallel motion begins. And it continues until the segment during which we want the region to shrink, as seen in Fig. 3.14.

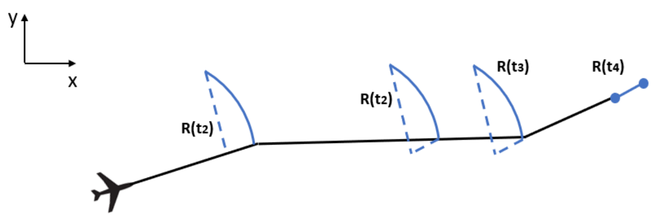
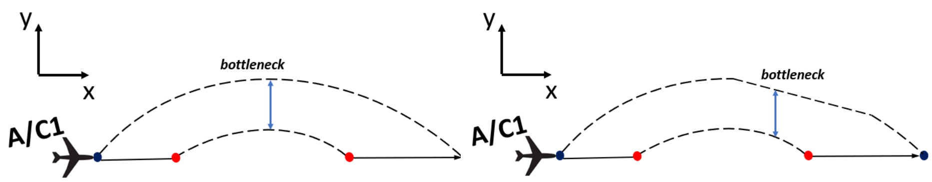


Figure 3.14: The evolution of a space region in a piece-wise linear trajectory.

3.5.3 Used Data Structures to Represent Moving Polygons & Complexity Analysis of Inter-Polygon Conflict Identification

Each spatio-temporal region is represented as an array of moving polygons. Each one of them representing the spatio-temporal part that an aircraft claims during one of the segments of its trajectory. A moving polygon, as explained above is an array of moving points. A moving point has an initial position, a velocity and a time interval during which it exists.
Detection of potential losses of separation between given regions can be performed through a brute-force approach, i.e. each pair of regions is checked. Such a procedure exhibits a computational complexity of $O((nrp)^2)$, where n is the number of aircraft that needs to be checked, r is the maximum number of regions each aircraft can have, and p is the maximum number of moving polygons each region can have. The core procedure used is the one that checks for conflicts between two moving polygons. This procedure has a computational



(a) Example 1. (b) Example 2

Figure 3.15: Illustration of the bottleneck for two regions.

complexity $O(s^2)$, where s is the maximum number of segments the polygon can have. The calculation of distances between the moving segments, as explained in the previous subsection, translates to the solution of some polynomial inequalities of second and forth order. The existence of analytic solutions for such cases [97] reduces their computational complexity to $O(c)$, where c is constant. The brute-force approach resulted in satisfactory runing times. The use, however, of more sophisticated methods (such as the hextree subdivisions methodology [99]) instead, could reduce the computational complexity for usual setups to $O(nrp)$ and $O(s)$ respectively[12].

3.6 Quantifying the Resilience of Spatio-Temporal Regions

We propose one metric per each region type in order to quantify resilience. To do so, we use the "tighter" part of the spatio-temporal region. We will call this part the bottleneck of the region.
The region implementation that avoids delays can be viewed as a 2D spatial segment that evolves over time. In this light, we define the bottleneck of a region of this type to be its shortest 2D segment within the conflict time interval. Two illustrative examples are given in Fig. 3.15.
Using the same point of view, spatio-temporal regions based on heading change, can be viewed as 2D surfaces evolving over time. In this case, we define the bottleneck of a region of this type to be the spatial surface with the smallest area.

[12]In the worst case of near identical trajectories, which is unlikely to happen in practice, the complexities will be $O((nrp)^2)$ and $O(s^2)$

3.7 Testing the Implementation Correctness of the Spatio-Temporal Regions through Simulations

In this section we describe the procedure followed to validate the spatio-temporal regions based on heading alteration. Similar procedures have been applied for the rest of implemented regions.
Velocities of different directions were used for different parts of the regions, therefore, we implemented the spatio-temporal regions through several sub-regions. A sub-region is a moving polygon, i.e. a set of points, each of which has an initial location, a constant velocity (in module and direction), and the time interval during which it exists.
To test the correctness of the implemented construction process of the proposed spatio-temporal regions for the treated scenarios, using an exhaustive generation of points, we simulated possible trajectories and checked if they lied inside the defined regions. More precisely, we created a class test-point, which contains 4D coordinates, a cumulative angle, and the accumulated delay. The 4D coordinates hold the current location of the point during the testing simulation, the cumulative angle holds the sum of all the angles that the test-point has performed so far in the simulation. An example is given in Fig. 3.16. The blue line is the initial trajectory. Point A lies on the initial trajectory, point B lies on the trajectory obtained after a turn of 30 degrees, point C lies on the trajectory obtained after taking another turn of 20 degrees, and point D lies at the trajectory obtained after performing another turn of -30 degrees. In this scenario the cumulative angle value is 0 degrees at point A, 30 degrees at point B, 50 degrees at point C, and 20 degrees at point D.
To calculate the accumulated delay of the scenario in Fig. 3.17, we used the following procedure: Let the blue line be the original trajectory of the aircraft and the black one the trajectory after some deviation is performed. Let B_1 be the projection of B in the original trajectory, and B_2 the location of the aircraft if it would have maintained its original trajectory. Further, let $\vec{V}$ be the original velocity, α the deviation angle, and dt_1 the time interval it took the aircraft to fly from point A to point B. Then the accumulated delay, denoted by d, at point B is:

$$d = \frac{|B_1 B_2|}{||\vec{V}||} = \frac{(||\vec{V}|| - ||\vec{V}\cos\alpha||)dt_1}{||\vec{V}||}$$

The generation of trajectories to be validated works as follows: We started from the initial state of the expanding sub-region, i.e. the first 4D point after which we are allowed to perform a maneuver. Discretizing in time by one second and in deviation angles by 5 degrees, we generated possible locations of the point, updating its cumulative angle and its accumulated delay. We performed this step recursively until an end point was reached, or until no more subsequent valid points existed, keeping the cumulative angle less then the maximum allowed (in our simulations it was 60 degrees) and the accumulated delay less than the

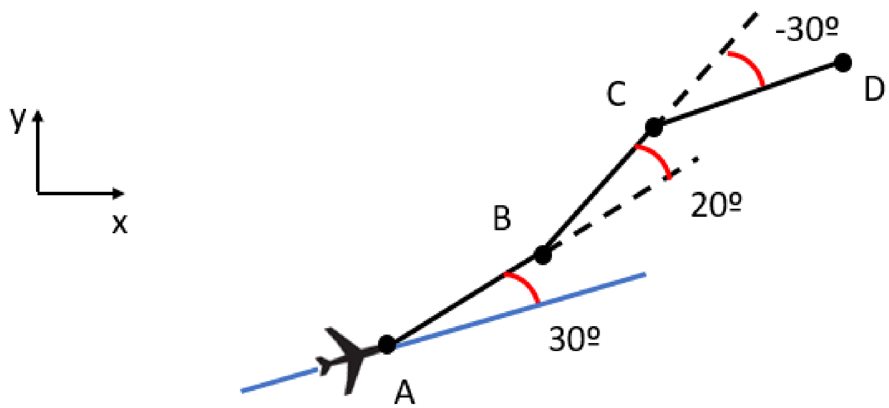


Figure 3.16: Example of an aircraft taking several turns.

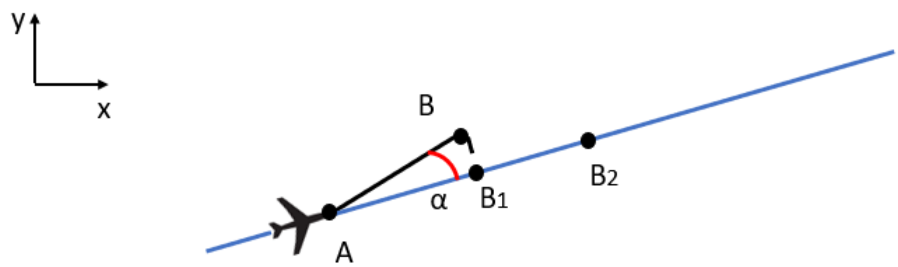


Figure 3.17: Example to illustrate accumulated delay.

maximum allowed delay (it can be calculated using the outer most deviation angle). For the regions to be correctly constructed, all the generated points need to lie within it.
We performed this procedure for the regions we generated in the treated traffic scenarios and in all cases the generated points lied within the corresponding spatio-temporal region. The data of the trajectories segments based on which the regions were built can be found here.

Chapter 4

Identification of Relevant Surrounding Traffic - The Aerial Ecosystem Formation

The first application of spatio-temporal regions we propose is related to the complete identification of relevant surrounding traffic. We propose in this chapter a two-step procedure, similar to [32], to detect aircraft that are relevant to a conflict resolution procedure. Different than [32], here the concepts of cluster and aerial ecosystem contain hierarchical structures. This, in combination with the use of spatio-temporal regions instead individual, discrete trajectories, allows for completeness in the relevant surrounding traffic identification.

4.1 Hierarchical Structures Over Aircraft

Both the cluster and the ecosystem are sets of aircraft based on pairwise spatio-temporal interdependencies. The concept of spatio-temporal interdependencies was the object of investigation in several European projects, such as PARTAKE [100] and AGENT [101]. Even though the time horizons and purpose of use vary between them, in both these projects two aircraft were declared interdependent if their assigned space-time regions (which can consist of a single trajectory, an assemble of trajectories, or some continuous space-time region) were closer than a certain threshold (different distance metrics were used in each project).
More concisely, let AC_i and AC_j be two aircraft which can be en route, or have a planned flight. Let R_i and R_j be the space-time regions assigned to AC_i and

AC_j respectively. Then:

$$AC_i \perp\!\!\!\perp AC_j \iff d_H(R_i, R_j) \leq H \land d_V(R_i, R_j) \leq V \tag{4.1}$$

where $\perp\!\!\!\perp$ stands for "interdependent", d_H, d_V are some functions that tells the minimum point-wise distance defined over the horizontal and vertical components of the regions respectively, and H and V are the required minimum horizontal and vertical separation.
Based on the concept of the interdependency, we will construct a hierarchical structure over aircraft. Let there be a potential conflict between at least two en route aircraft. We will denote the set of aircraft involved in this conflict by C and define a hierarchy H_C over the traffic, based on C. The members of the first order of H_C are the members of C. Members of the i^{th} order, where $i \neq 1$, are the aircraft that are not members of a lower order, but have an interdependency with a member of the $(i-1)^{th}$ order. Formally, given that H_C is the defined hierarchy, and $H_C(i)$ is the set of members of the i^{th} order of this hierarchy, we define:

$$\begin{cases} H_C(1) := & C \\ H_C(i) := & \{\mathrm{AC} \in F | \mathrm{AC} \in H_C^-(i) \land (\exists \mathrm{AC}' \in \\ & H_C(i-1) : \mathrm{AC} \perp\!\!\!\perp \mathrm{AC}')\} \end{cases} \tag{4.2}$$

where F is the set of all aircraft we can consider, and $H_C^-(i) := F \setminus \cup_{j=1}^{i-1} H_C(j))$. In other words, H_C contains at its first order the preselected set of aircraft C. At its second order it contains aircraft which are not members of the first order, but have at least an interdependency with a member of the first order. In the third order we find aircraft that are not members of the first, or second order, but have at least one interdependency with a member of the second order. The logic goes on recursively.

4.2 Cluster Identification

Concrete implementations of the hierarchical traffic idea, defined above, depend on concrete implementation of the spatio-temporal regions we use to define the interdependencies. Let F denote the set of aircraft we will consider and AC_i and AC_j be two aircraft in it. Let further B_i and B_j be two spatio-temporal boxes constructed respectively around the trajectories of AC_i and AC_j, big enough to contain all the possible locations of the aircraft after feasible maneuvers are possibly performed. Then:

$$AC_i \perp\!\!\!\perp_{cl} AC_j \iff d_H(B_i, B_j) \leq H \land d_V(B_i, B_j) \leq V \tag{4.3}$$

where $\perp\!\!\!\perp_{cl}$ stands for "dependent on clustering level" and d_H, d_V, H, V are defined as in Def. 4.1.
In Fig. 4.1 an example is given, by representing the horizontal components (x and y) of the spatio-temporal boxes. We assume that all vertical components

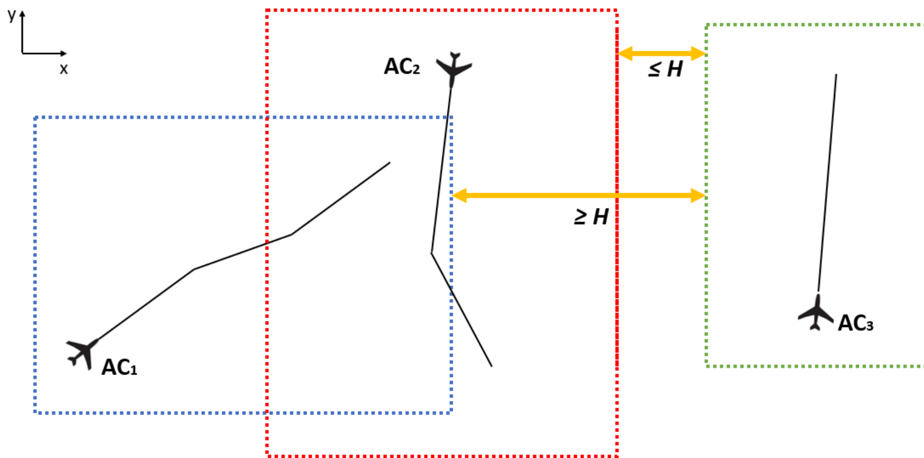


Figure 4.1: Example to illustrate cluster pairwise interdependencies.

are identical (hence there is a loss of vertical separation between the boxes). In this example, the blue box is the box of AC_1, the red one of AC_2 and the green one of AC_3. There is a cluster-level interdependency between AC_1 and AC_2 since their boxes overlap (therefore their distance is 0). Moreover, AC_2 and AC_3 are also interdependent at cluster level, since their distance is less than the minimum required separation H. However, no cluster-level interdependency exists between AC_1 and AC_3. This holds true because their horizontal distance is longer than H.

Based on the given interdependency definition (4.3), and the hierarchy definition (4.2), we will construct the hierarchical structure over aircraft, called cluster. Let there be a potential conflict between at least two en route aircraft. We will denote the set of aircraft involved in this conflict by C. Members of C then, are members of the first order of the cluster. Members of the i^{th} order, where $i \neq 1$, are the aircraft that are not members of a lower order, but have an interdependency with a member of the $(i-1)^{th}$ order. Formally, given that Cl is the set of cluster members and $Cl(i)$ is the set of cluster members of the i^{th} order, we define:

$$\begin{cases} Cl(1) := & C \\ Cl(i) := & \{\text{AC} \in F | \text{AC} \in Cl^-(i) \wedge (\exists \text{AC}' \in \\ & Cl(i-1) : \text{AC} \perp\!\!\!\perp_{cl} \text{AC}')\} \end{cases} \tag{4.4}$$

where $Cl^-(i) := F \setminus \cup_{j=1}^{i-1} Cl(j))$.

In the example of Fig. 4.1, if we assume that AC_1 is a conflict aircraft[1], but

[1] We assume AC_1 is in conflict with aircraft AC_0. AC_0 is not depicted in Fig. 4.1

AC_2 and AC_3 are not, then AC_1 will be a member of the first order, AC_2 a member of the second order and AC_3 a member of the third one.

4.3 Aerial Ecosystem Identification

The cluster structure, from the way its interdependencies are constructed, is too conservative. The use of spatio-temporal boxes, even though it is computationally efficient, results in an overestimation of the relevant aircraft of a given scenario. In order to provide a better estimation of the scenario complexity and the interdependencies between the aircraft, we introduce here the "ecosystem" structure. The difference between a cluster and its corresponding ecosystem lies on the nature of their interdependencies. While to construct a cluster, spatio-temporal boxes were used, as a mean of approximating the results of performing some maneuvers, to construct an ecosystem we will check the actual possible maneuvers.
Let F be the set of all aircraft we will consider. Let $tr(AC_k)$ denote the original trajectory of an aircraft AC_k in F, and M_k the set of possible maneuvers for AC_k. Furthermore, let $tr(AC_k, m)$ be the modified trajectory of AC_k after performing a maneuver $m \in M_k$. Then, given two aircraft AC_i and AC_j from F and their corresponding set of possible maneuvers M_i and M_j,

$$\begin{aligned} AC_i \perp\!\!\!\perp_{ec} AC_j \iff \exists m_k \in M_i, m_l \in M_j : &\text{conf}(AC_i, \\ &AC_i, m_k, m_l) \end{aligned} \tag{4.5}$$

where $\perp\!\!\!\perp_{ec}$ denotes an "interdependency in ecosystem level" and conf(AC_i, AC_j, m_k, m_l) denotes that aircraft AC_i and AC_j will be in conflict if they perform maneuvers m_k and m_l respectively.
Spatio-temporal regions become relevant in the calculation of interdepedecies at the ecosystem level. Instead of considering all possible pairs of trajectories, it is enough to check for an inter-regional conflict, between regions that include all possible maneuvers for each aircraft. This will suffice to consider all physically feasible simple heading maneuvers that a CD&R system can issue. Note that, while both the spatio-temporal regions proposed in the clustering procedure (i.e. the spatio-temporal boxes) and the ones proposed here contain all feasible heading maneuvers, the spatio-temporal boxes claim a lot of extra space which the aircraft cannot actually utilize.
Given the ecosystem interdependency definition, the ecosystem can be also defined. Let Cl be a given cluster. The aircraft which are first order members of the cluster are also first order members of the ecosystem. Members of the i^{th} order, where $i \neq 1$, are the aircraft that are members of $Cl(i)$ and that exists an ecosystem member of $(i-1)^{th}$ order with which they have an interdependency at the ecosystem level. Formally, if Ec is the set of ecosystem members and $Ec(i)$ the set of ecosystem members of i^{th} order, then:

$$\begin{cases} Ec(1) := Cl(1) \\ Ec(i) := \{\text{AC} \in Cl(i) | (\exists \text{AC}' \in Ec(i-1) : \text{AC} \perp\!\!\!\perp_{ec} \text{AC}')\} \end{cases} \tag{4.6}$$

An ecosystem can be clearly defined directly in a given traffic, without the need of a corresponding, predefined cluster. however, identifying pairwise interdependencies through the brute force approach described in the previous chapter, i.e checking all pairs of aircraft, the use of a cluster comes with high computational advantages. Nontheless, the introduction, however, of more sophisticated techniques, like the hextree subdivisions [99] can vanish this advantage and even increase further the computational efficiency. In such a scenario, the ecosystem structure can be constructed directly from the traffic, without the cluster structure being a mediator.
Note that, because of the more complex structure of the ecosystem windows, which are changing shape in time, a schematic representation, similar to the one provided in Fig. 4.1 for the cluster case, could be misleading. We therefore, decide not to provide one.

4.4 Defining Completeness of Relevant Traffic Identification

So far we have discussed completeness informally. Here, we give a formal definition of completeness.
Let T be the set of flying aircraft during a time period of interest and $AC_1, AC_2 \in T$ two flying aircraft that are in conflict with each other. Let $R_r \subseteq T$ be the set of all aircraft among which a conflict can arise, within a given time horizon, in case the initial conflict between AC_1 and AC_2 is resolved. Moreover, let CR_p be a pairwise conflict resolution procedure and R_{crp} be the set of aircraft that need to be considered during the resolution process in order to not induce a new conflict within the time interval $[t_1, t_2]$. Finally, let I_p be a procedure that, given the traffic T and the two conflict aircraft AC_1 and AC_2, identifies a set R_i of relevant aircraft.
We define four notions of completeness as follows:

- I_p is *complete with respect to* CR_p if and only if:

$$I_p \models CR_p \iff R_{crp} \subseteq R_i \tag{4.7}$$

  where $\models$ indicates *completeness with respect to*

- I_p is *tightly complete with respect to* CR_p if and only if:

$$I_p \vdash CR_p \iff R_{crp} = R_i \tag{4.8}$$

  where $\vdash$ indicates *tight completeness with respect to.*

- I_p is *universally complete* if and only if:

$$\forall CR_p, I_p \models CR_p \tag{4.9}$$

  i.e. I_p is complete with respect to every possible conflict resolution procedure.

- I_p is *universally tightly complete* if and only if $R_i = R_r$.

The definition of the aerial ecosystem structure implies it is tightly complete. In practice, given we are using a certain conflict resolution procedure CR_1, we would prefer a surrounding traffic identification procedure I_1 which is tightly complete with respect to CR_1 and not necessarily universally tightly complete. In this way the amount of aircraft that need to be considered is minimized, while no induced conflict can arise within the given time window $[t_1, t_2]$.

4.5 Simulation Evindence of the Advantages of the Ecosystem over the Cluster

The hypothesis we raised was that an ecosystem has significantly less members than the corresponding cluster. In order to support our argument, we ran simulations with real and predicted traffic.

4.5.1 Data and the Parameters Used

We perform the evaluation using traffic data from Eurocontrol's Demand Data Repository II (DDR II). We present two scenarios, one with real historical traffic from 12.02.2019 and another one with synthetic dense traffic generated using Eurocontrol's STATFOR[2]. The synthetic traffic was used in order to investigate scalability through aerial ecosystems with more members. The predicted traffic is a high density estimate on the date 10.09.2021. In both scenarios, we consider en route conflicts around London TMA, more specifically aircraft flying between 51.01 and 52.05 degrees of latitude, -0.85 and -0.14 degrees of longitude and above flight level 245 (i.e. above 24500 feet).
Conflicts are detected using a methodology based on the proposal in [102]. As soon as a conflict is detected, the originally planned trajectory of each involved aircraft is filtered from five minutes before entering the conflict interval, until two minutes after exiting the conflict interval. The time length of the cluster is therefore seven minutes plus the length of the conflict. Fig. 4.2 illustrates the planar cluster window. For each geographic direction (North, South, East, West) we take the furthest waypoint and add to it 25 NM[3]. The vertical cluster window, which is not illustrated in Fig. 4.2 for clarity reasons, is formed in a similar manner with a margin of 3000 feet[4]. We extend both clusters and ecosystems up to a third level. On ecosystem level, the time window is kept the same as in the cluster case and a maximum deviation angle of 60 degrees is used to construct the aircraft's space-time regions. Three regions are build for each aircraft, region "left" bounded by aircraft's original trajectory and its leftmost trajectory that the aircraft can achieve, given its configuration, region

[2]STATFOR is a tool that predicts future traffic demand based on the current one and airport constraints

[3]Other values were also tested and resulted in drastic reduction of the number of members.

[4]Both spatial values were chosen based on experimentation

"right" bounded by aircraft's original trajectory and its rightmost trajectory it can achieve given its configuration, and region "straight" including only the original trajectory of the aircraft.
To check if a pair of aircraft has an interdependency at cluster, or ecosystem level, a brute-force approach was used and each pair of aircraft was investigated. This procedure exhibits a computational complexity of $\Theta(n^2)$, where n is the number of aircraft we consider. This performance can significantly be improved by the use of more sophisticated techniques, as the hextree subdivision method [99], which displays a computational complexity of $\Theta(n)$ on usual setup and $\Theta(n^2)$, in the unlikely case of having near identical trajectories.

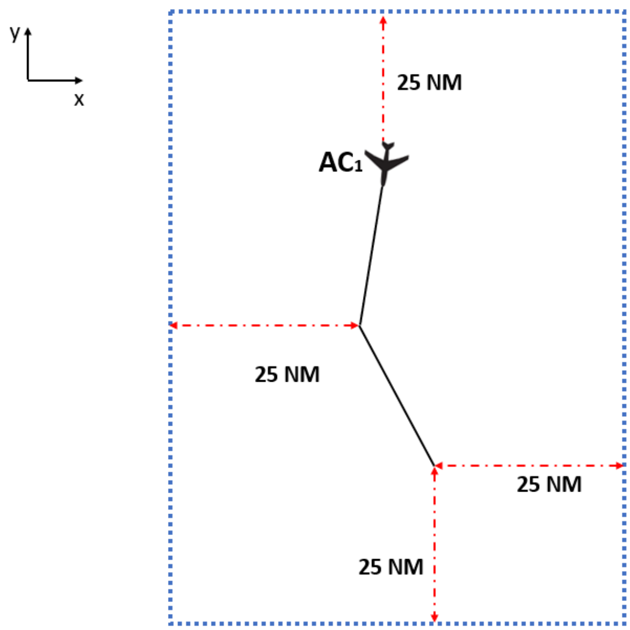


Figure 4.2: The planar part of the cluster box.

4.5.2 Comparison of Clusters to the Ecosystems

3306 conflicts, out of which 3275 were not overheadings, were detected in the historical traffic scenario and 12848 conflicts, out of which 12746 were not overheadings, were detected in the futuristic traffic scenario. An analysis was performed for all the detected cases, however 2000 conflicts were sampled from each scenario and used to construct the histograms provided in this section.
Fig. 4.3 contains the histogram of the identified clusters in the scenario with the historical traffic, while Fig. 4.4 contains the histogram of the corresponding

ecosystems. In the clustering step[5], 7.25% (i.e. 145 out of 2000) of the clusters have more than forty members each and 37.35% of them (i.e. 747 out of 2000) have only two members. The corresponding ecosystems have a maximum of six members, found in three cases, and 90.3% of the total amount (i.e. 1806 out of 2000) have only two members. The reduction is drastic.

The futuristic scenario exhibits a similar reduction tendency, where in the

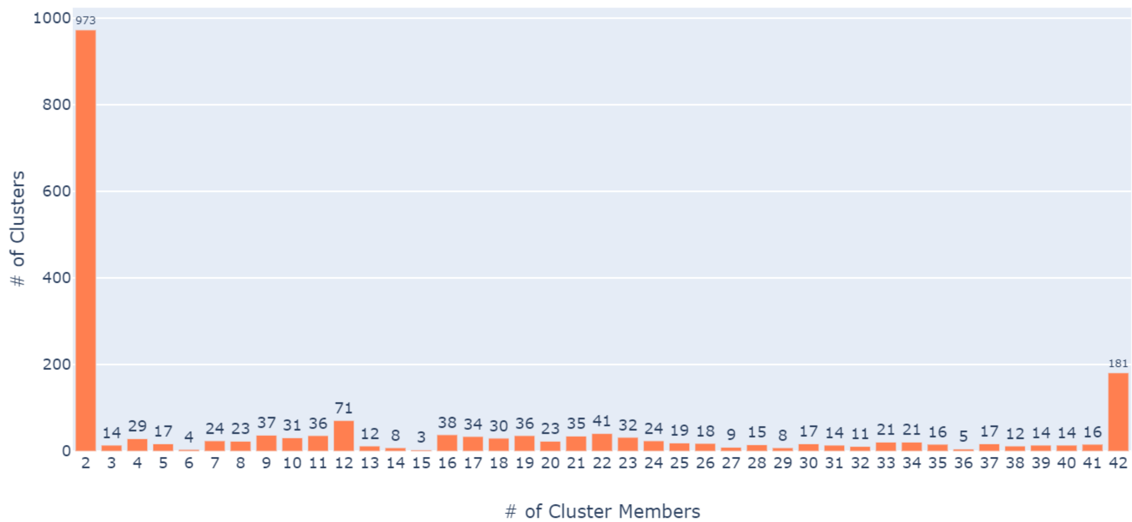


Figure 4.3: Histogram of clusters identified in the historical traffic.

clustering case we have 7.25% (i.e. 145 out of 2000) of the clusters with more than forty members and 34.9% (i.e. 698 out of 2000) of them with two members only. The corresponding ecosystems have a maximum of seven members in ten cases and 88.55% (i.e. 1771 out of 2000) of the total with only two members.

What the clustering structure does essentially is count the amount of aircraft flying in a given space-time volume relevant to a detected conflict. In this sense, the number of cluster members is a measure similar to the dynamic aircraft density. An interesting observation, in both scenarios, is that even though the clustering structure can have significantly large amount of members, counting the possible dependencies that can come by performing feasible maneuvers of the aircraft through the ecosystem structure, reduces drastically the amount of aircraft that need to be considered in a conflict resolution procedure.

4.5.3 Analysis of an Ecosystem for Each Simulated Traffic

Going further than the number of members of each structure, the dependencies between various regions used in the ecosystem can give us a deeper insight. Two ecosystems, each with 7 members are analyzed and compared for this purpose.

[5] As noted before, clusters are extended up to a third level.

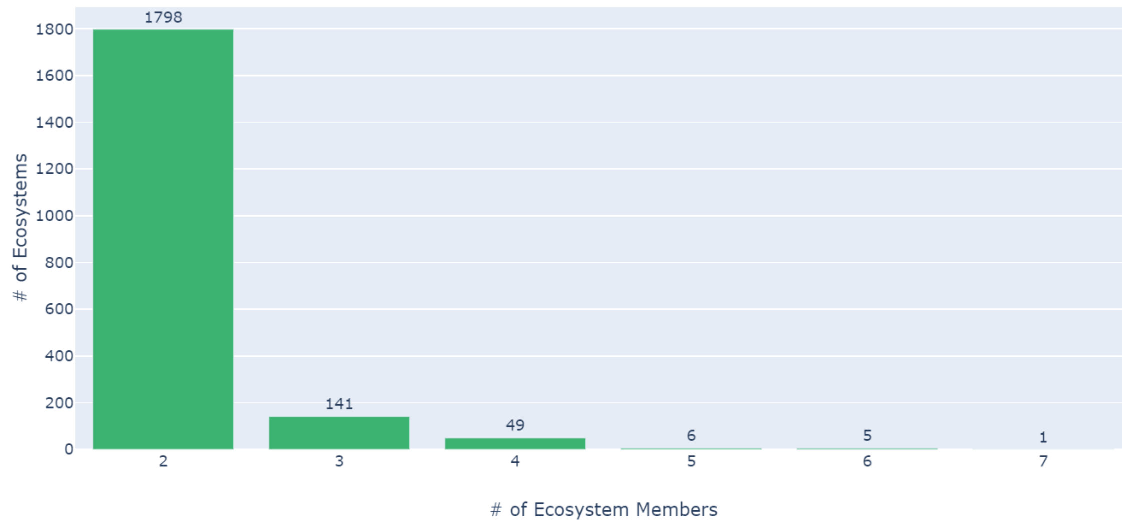


Figure 4.4: Histogram of ecosystems identified in the historical traffic.

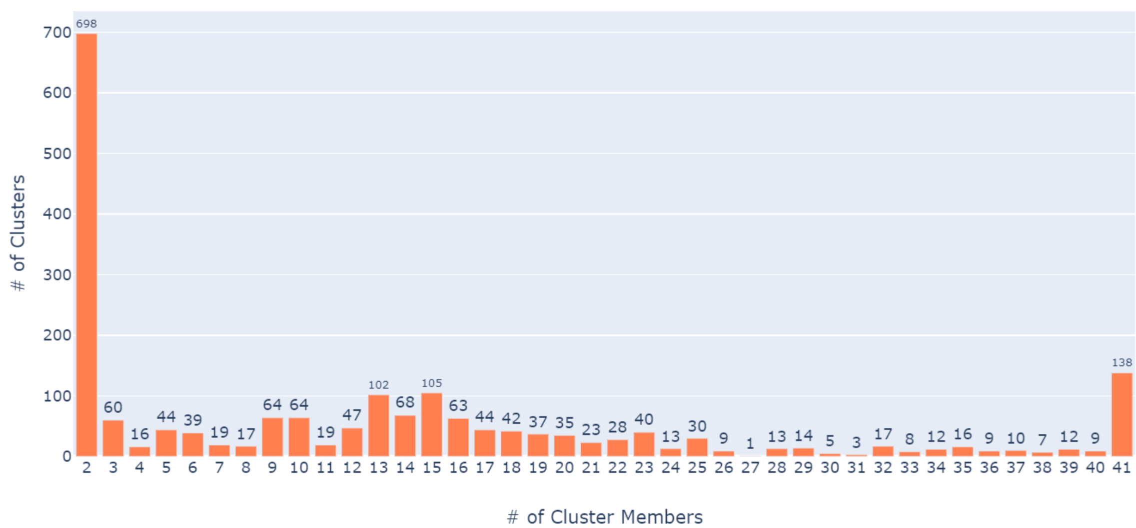


Figure 4.5: Histogram of clusters identified in the futuristic traffic.

A similar analysis can be also performed at the cluster level. However, the over-conservative approached by which the clusters are constructed, would result in minimal insights.
The first ecosystem is taken from the historical traffic. The corresponding cluster contains 39 members, 2 of which of the first order, 23 of the second, and

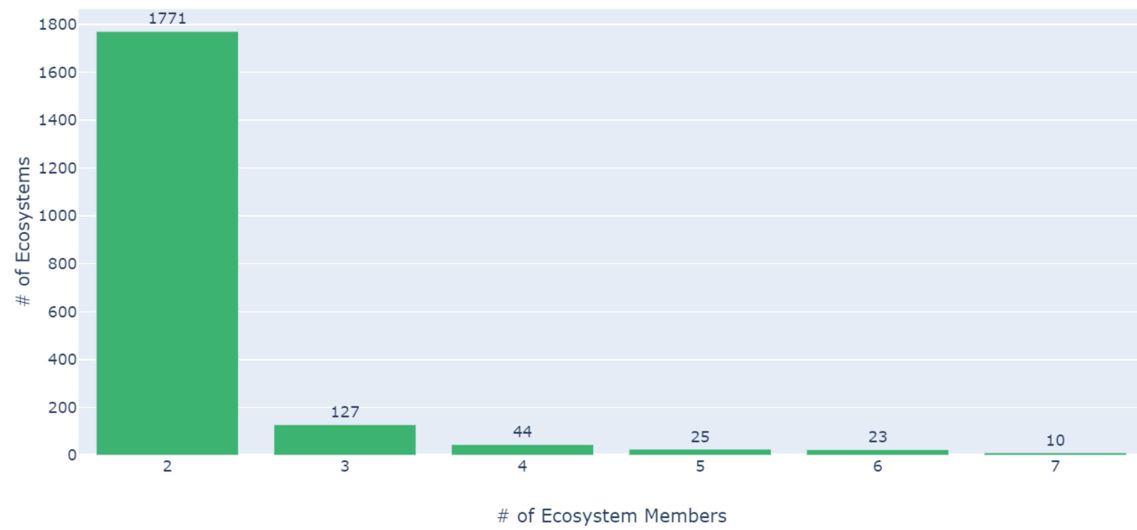


Figure 4.6: Histogram of ecosystems identified in the futuristic traffic.

14 of the third one. The members of the ecosystem are classified in 2 members of the first order, 3 of the second, and 2 of the third one. Fig. 4.7 shows the graph of interdependencies for ecosystem 1. Each node of the graph represents an aircraft of the ecosystem. Two nodes are connected via a dashed edge if the respective aircraft are in conflict. Otherwise, the are connected through a continuous edge if there exist an interdependency between them at ecosystem level, i.e. if there exist a pair of feasible maneuvers, one for each aircraft, that can put them into conflict. For example in a certain scenario a left maneuver of AC_1 could result in a loss of separation with AC_3. In this case, AC_1 and AC_3 are declared interdependent and the vertices that represent them in the graph of the interdependencies are connected through an edge. We see that even though there are 7 members, they are loosely connected to each other and the chances of finding an efficient solution quickly are high. Moreover, as explained earlier, an edge between aircraft AC_a and aircraft AC_b is present in the the graph of interdependencies if some combination of maneuvers exist to put the two aircraft in conflict. This means that if we reduce the maneuverability of the aircraft, some of edges can be removed. More specifically, if we constraint ourselves to resolutions where maneuvering only the conflict aircraft (one of them or both), the graph of inter dependencies will contain less edges, as depicted in Fig. 4.8. According to that graph, we can see that AC_2 can perform a maneuver without inducing a new conflict, given that all other ecosystem members maintain their original trajectories.

The situation is different for ecosystem 2, the ecosystem extracted from the futuristic scenario, even though it also has 7 members. The corresponding cluster contains 35 members (i.e. less than the 39 members in the first case), 2

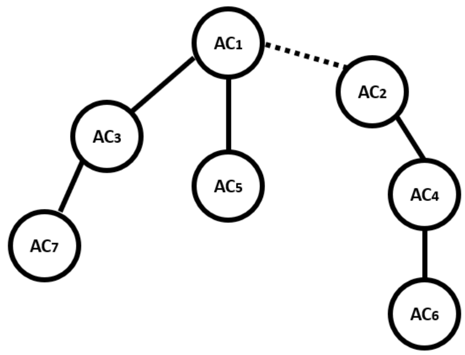


Figure 4.7: Graph of ecosystem 1 in the historical traffic.

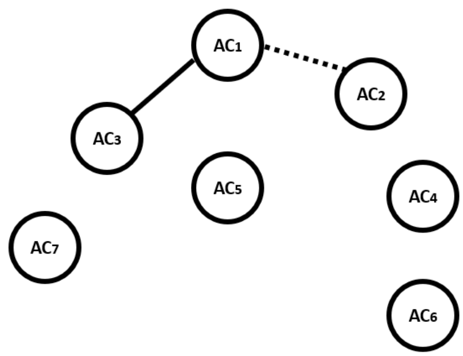


Figure 4.8: Graph of ecosystem 1 constrained to single-maneuver-solutions.

of which are of the first order, 18 of the second, and 15 of the third one. The members of the ecosystem are classified in 2 members of first order, 4 of the second order, and 1 of the third order. Moreover, as shown in Fig. 4.9 the graph of interdependencies is denser, almost fully connected. Constraining to single maneuver solutions, reduce the number of aircraft we need to consider, but still leaves the rest of the members heavily connected, Fig. 4.10. Therefore, solving this ecosystem is not as straightforward as solving the previous one.

The above comparative analysis hints the power that spatio-temporal interdependencies, based on only feasible maneuvers of the aircraft, have.

4.5.4 Further Results Regarding the Ecosystem Depth

The maximum depth found in the treated scenarios was 4. In order to see how the maximum depth alters, as traffic gets denser, we generated more synthetic traffic scenarios. More specifically, we congested the used, real traffic by compressing its flight levels, once by 25%, and then by 50%. Since we are interested

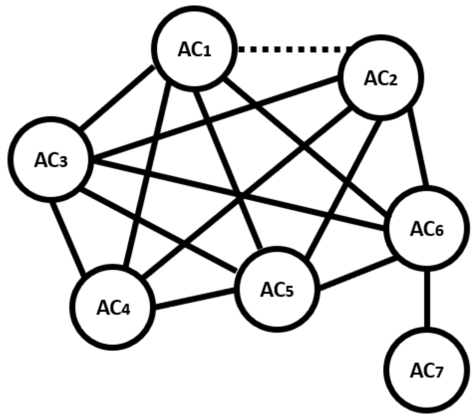


Figure 4.9: Graph of ecosystem 2.

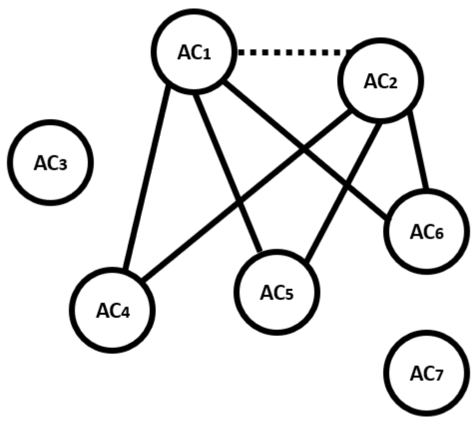


Figure 4.10: Graph of ecosystem 2 constrained to single-maneuver-solutions.

in en route traffic conflicts, We compress the flight level (FL) of waypoints only if it is above 250 (i.e. 25000 feet), otherwise we keep the flight level as is. We preferred these scenarios to evaluate the ecosystem's depth in more extreme circumstances.

Fig. 4.11 shows a histogram of the depth for each of the initialized ecosystems for the original traffic, the traffic compressed by 25% and the traffic compressed by 50%. For the original traffic, we see that the maximal depth is four, while most ecosystems have a maximal depth of one. This behavior is preserved also in both compressed traffic scenarios, where most ecosystems have a maximal depth of one.

The maximal depth increases, however, this increment is smaller than expected. As we can see, the majority of the ecosystems have a depth of three,

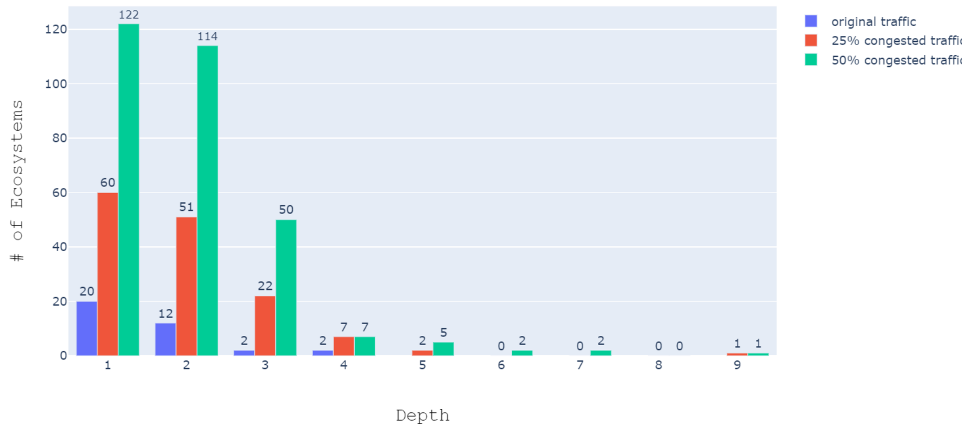


Figure 4.11: Histogram of the maximum depth of all ecosystems for all traffic.

while there is one ecosystem for each compressed traffic scenario, which has a depth of nine. This shows that aircraft are spread in such a way that the depth of ecosystems doesn't blow up. It also serves as evidence that the constructed spatio-temporal regions use space-time in an efficient manner.

Chapter 5

Compound Ecosystems

The so far given ecosystem definition is based on a single pairwise conflict. We will refer such ecosystems, as simple ecosystems. As the results from Chapter 4 hint, the depth of simple ecosystems does not increase dramatically, as traffic density increases. However, what happens is that a significant amount of conflicts are found nearby and their corresponding, simple ecosystems might coexist in time with tight spatial bounds. A methodology therefore, to identify such cases is mandatory.

5.1 Compound Ecosystem Formation

Let ec_1 and ec_2 be two simple ecosystems, $[t_{s1}, t_{e1}]$, $[t_{s2}, t_{e2}]$ their respective time intervals, and S_1, S_2 be their corresponding set of members-aircraft. Then ec_1 and ec_2 are dependent in case their time intervals overlap and they contain some common members.

Formally, let ec_1 and ec_2 be two ecoystems and t_1, $[t_2$ be the time intervals during which each ecosystem exists. Furthermore, let EC_1 and EC_2 be the set of aircraft members of ecosystems ec_1 and ec_2 respectively. Then,

$$ec_1 \perp\!\!\!\perp_c ec_2 \iff t_1 \cap t_2 \neq \emptyset \wedge EC_1 \cap EC_2 \neq \emptyset \tag{5.1}$$

where $\perp\!\!\!\perp_c$ denotes an interdependency between ecosystems.

We will define a compound ecosystem based on pairs of merged simple ecosystems. More specifically, let G be a defined graph, where each node represents a simple ecosystem and each edge represents a dependency between two simple ecosystems. We define a compound ecosystem to be a connected component in the created graph G, that contains at least two ecosystems.

Fig. 5.1 illustrates the definition. We see that there are 6 initialized ecosystems. Moreover, there are some dependencies detected. Specifically, there is a dependency between ec_1 and ec_2, another between ec_2 and ec_3, and a last one between ec_4 and ec_5. Based on these dependencies two compound ecosystems

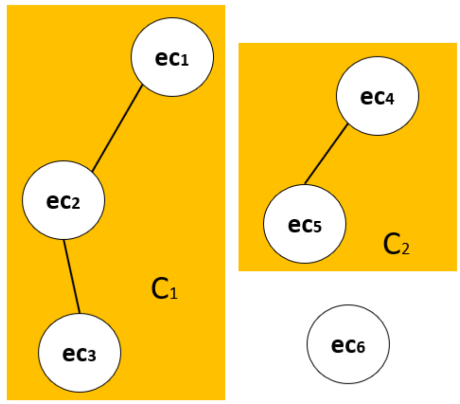


Figure 5.1: Illustration of two detected compound ecosystems, and an isolated simple ecosystem.

are formed. the first one, C_1 contains the members of ec_1, ec_2, and ec_3, while the second, C_2 contains the members of ec_4 and ec_5. Note that, ec_6 is an isolated, simple ecosystem.

5.2 Decomposition Strategies

Given the definition and the hierarchical nature of the compound ecosystems, there are different ways a decomposition can be constructed. We propose four simple strategies, which we will elaborate in the following paragraphs. The purpose of attempting to perform such decompositions is to decrease the combinatorial complexity that conflict resolvers will face.
We first consider the amount of time overlap. If it is less than 10% for either of the ecosystems, we cut the overlapping time interval from the duration of the ecosystem that starts later. This choice is based on the way we construct the ecosystems, i.e. we gather data from 5 minutes before the conflict and 2 minutes after the conflict. Illustration of how the time overlap is calculated is shown in Fig. 5.2a.
Through the second strategy, we will constrain the considered depth of the ecosystems in the sought solutions. This strategy can tackle two types of scenarios. Firstly, cases when none of the common members are conflict aircraft. Secondly, cases when there is a common member that is a conflict aircraft, however its order on the remaining ecosystems is higher than 2. Fig. 5.2b illustrates a scenario where such a strategy can be applied. The conflict pairs are $AC_1 - AC_2$ and $AC_4 - AC_5$. The only common member between the two simple ecosystems is AC_3. Fig. 5.2c shows a scenario when the common member is a conflict member in one of the simple ecosystems. AC_5 is in conflict with AC_6 and thus a first order member of that simple ecosystem, but it's a member of

order 4 for the other ecosystem. In this case, constraining the depth of that simple ecosystem, will allow us to consider each ecosystem separately.
When this is not the case, we attempt to use the third strategy. Here, we attempt to solve the ecosystems by not moving the common, conflict member. In doing so, we restrict the solution in such a way that each ecosystem is solved by moving the non-common members, thus minimizing how the solution of one ecosystem affects the other. A toy example, where this strategy can be applied is presented in Fig. 5.2d. There, we constrain AC_2 and by maneuvering AC_1 and AC_3, both conflicts can be solved independently.

Finally, if no solution has been found by considering any of the above strate-

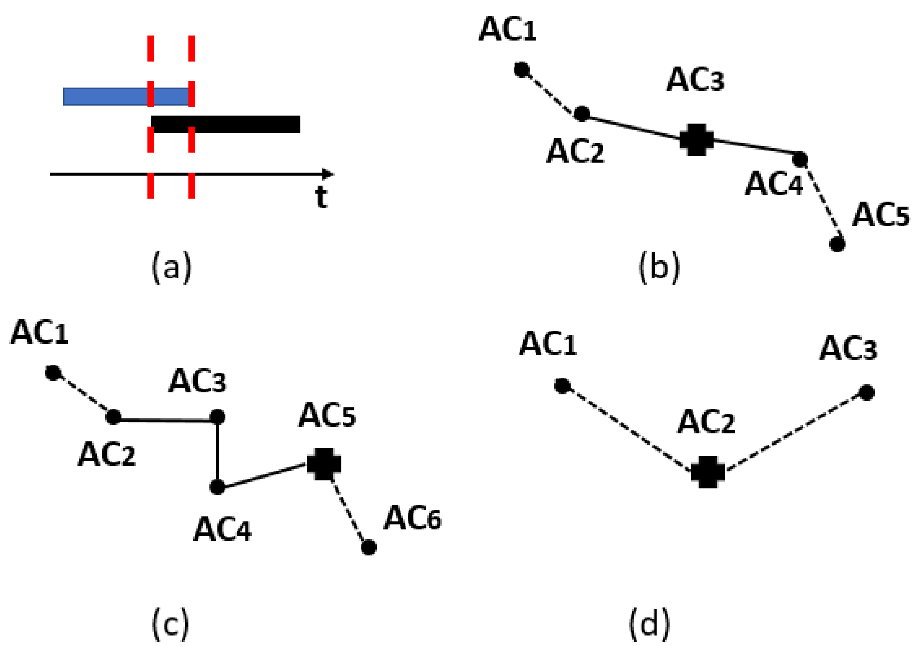


Figure 5.2: One illustrating scenario for each strategy.

gies, the compound ecosystem will have to be considered as a whole. This means that we will have to treat situations with more than one conflict present.

5.3 Simulation Results

5.3.1 Data and the parameters used

We evaluate our work using traffic data from Eurocontrol's (DDR II). The real historical traffic is from 12.02.2019. Furthermore, we simulate more congested traffic by compressing the flight level once by 25%, and then by 50%. Since we

are interested in en route traffic conflicts, We compress the flight level (FL) of waypoints only if it is above 250 (i.e. 25000 feet), otherwise we keep the flight level as is.
Conflicts are detected using a methodology based on the proposal in [102], with an added filter to discard conflicts that are found bellow FL250. As soon as a conflict is detected, the planned trajectory of each involved aircraft is filtered from five minutes before entering the conflict interval until two minutes after exiting it. Thus, the duration of the ecosystem is seven minutes plus the duration of the conflict.

5.3.2 Compound Ecosystems

In this section, we present and discuss results regarding compound ecosystems. Table 5.1 shows an overview of ecosystems present in all traffic scenarios, as well as the effectiveness of each strategy to decompose the compound ecosystems.
In the original traffic, there 36 ecosystems present, where 6 are not isolated and form 3 compound ecosystems. All cases could be tackled using the third strategy. These attempts proved to be successful, thus there was no need to consider joining the involved ecosystems.
When compressing the flight level by 25%, we notice an increase in the number of total **ecosystems**, **not isolated ecosystems** and **compound ecosystems**. We solve 5% of the compound ecosystems by following the first strategy, and 20% by following the second. The majority, 60%, of the compound ecosystems could be solved by utilising the third strategy, while 40% need further consideration. A similar qualitative behaviour is noticed also when compressing flight level by 50%. In this case, less compound ecosystems can be decomposed following the proposed strategies. This comes as a result of more complex geometries and stronger interdependencies that arise from compressing the traffic at such scale. However, it must be noted that the majority of compound ecosystems can still be decomposed by using one of the strategies proposed in our work.

Table 5.1: Ecosystem statistics and strategy performance for each traffic.

				Strategies			
Traffic	**Simple Ecosystems**	**Not isolated Ecosystems**	**Compound Ecosystems**	**Cut in time (%)**	**Cut in level (%)**	**Move one (%)**	**Join ecosystems (%)**
Original	36	6	3	0	0	100	0
25% congested	143	49	20	5	20	60	40
50% congested	303	120	49	10.2	8.16	51.02	48.08

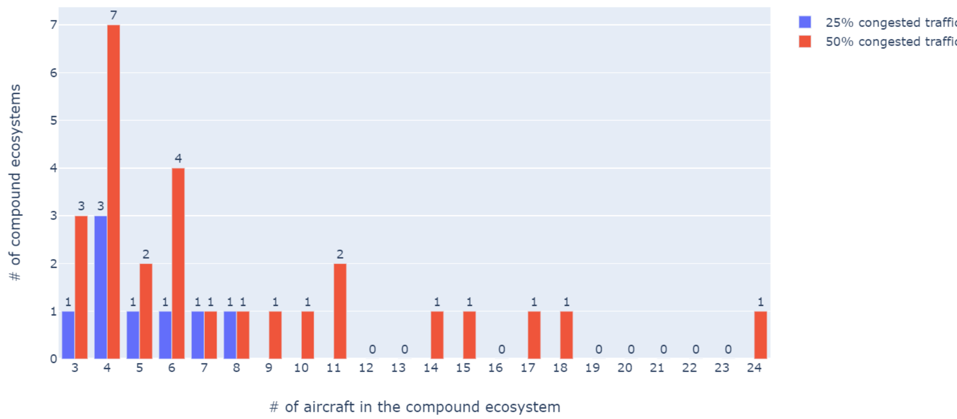


Figure 5.3: Histogram showing the number of aircraft in compound ecosystems, which we were not able to solve using one of the proposed strategies, for the simulated congested traffic.

In Fig. 5.3, we show a histogram of the number of aircraft in the compound ecosystems that we were not able to solve using one of the proposed strategies. As the original traffic did not contain such ecosystems, we show the results only for the simulated traffic. As can be seen, for both situations, the majority of compound ecosystems that could not be solved have 4 aircraft. This can be related to the fact that most ecosystems have a depth of one (i.e., 2 aircraft). As expected, the denser traffic shows more variety in the number of aircraft present in compound ecosystems. As stated earlier, such behaviour is the result of aircraft being closer to each other, which leads to bigger ecosystems.

5.3.3 Analyzing two Complex Compound Ecosystems

There is a wide range of geometries among the detected compound ecosystems on which our strategies of decomposition did not work. In this section, we present two examples, one that can be managed partially with our strategies, and another that cannot. Both situations were found in the denser simulated traffic.

Fig. 5.4 shows the graph of the first example. There are 4 present conflicts in this compound ecosystem. The case cannot be fully decomposed. However, if we look closely, we can see that conflict aircraft BAW955L, on the upper left corner, has no other interdependency than the conflict one. This means that this aircraft can find maneuvers to solve its conflict, while the other conflict aircraft keeps its original trajectory. Also conflict aircraft RYR7ME, also on the upper left corner, apart from the conflict interdependency, has only a single other interdependency with aircraft EVA067, which has no other interdependencies. So using these 2 aircraft we can achieve another conflict resolution.
Moreover, cutting the rest of the graph at aircraft UAE3PG (center of the figure), can make the other 2 conflicts independent of the 2 treated ones. In such

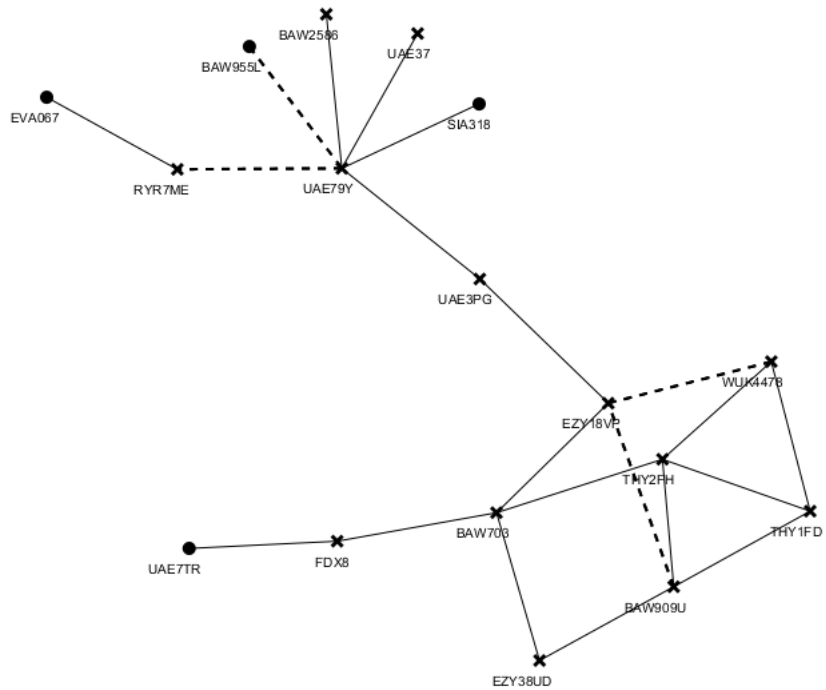


Figure 5.4: Example of a partially decomposable compound ecosystem. Conflicts are shown with dashed lines and common members are denoted with a cross.

a case, we will be left with 2 conflicts to solve, instead of 4, and 8 aircraft to consider, instead of 16.

Fig. 5.5 illustrates the graph of the worst detected compound ecosystem. We find 11 conflicts in it and 24 aircraft in total. In this scenario none of our strategies can help reducing complexity and the compound ecosystem needs to be treated as a whole. Realistically, such situation is not expected to occur in any projected, future scenario. Nevertheless, alternative decomposing strategies, or solutions by considering it as a whole need to be sought.

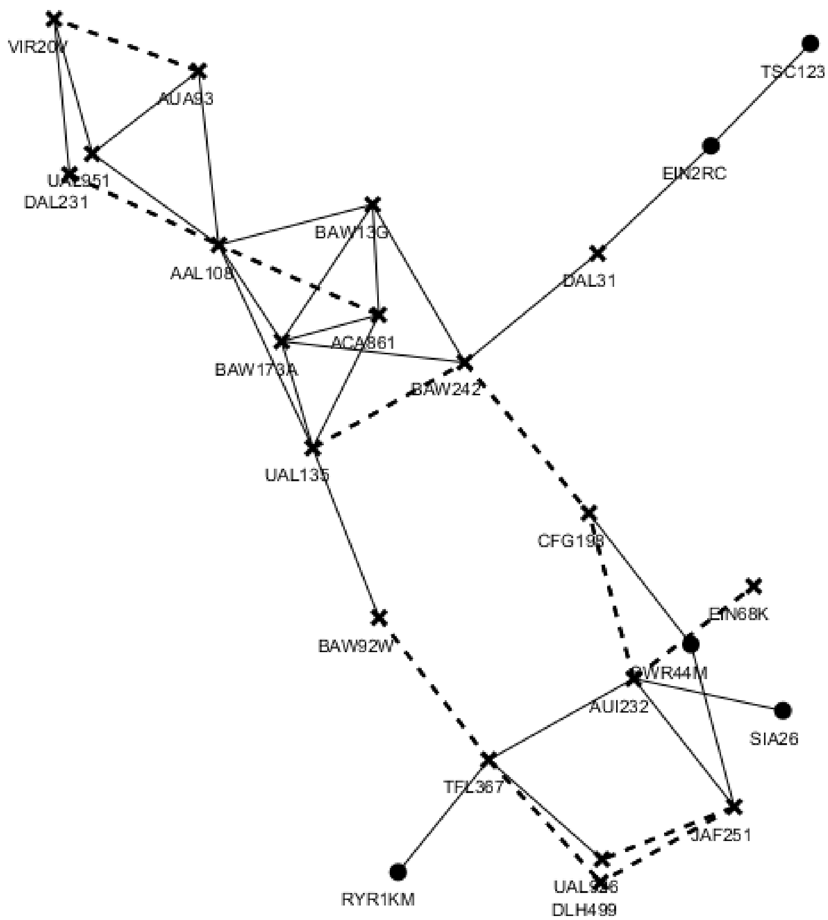


Figure 5.5: Example of a non decomposable compound ecosystem. Conflicts are shown with dashed lines and common members are denoted with a cross.

Chapter 6

Conflict Resolution Maneuvering a Single Aircraft Based on Spatio-Temporal Regions

In this chapter we will present how spatio-temporal regions can be used to perform CR by maneuvering a single aircraft only. Solving conflicts in such a way generates less perturbations on the system and are easier to manage. Clearly, such resolutions are not always possible and that's why we use our framework to provide resolutions by maneuvering more than one aircraft in Chpater 7. We constructed spatio-temporal regions in Chapter 3 in two manners. To achieve CR, some methodologies to cut spatio-temporal regions, in order to make them safe, need to be implemented.

6.1 Conflict-Free Spatio-Temporal Regions

This approach supports both types of regions defined in Chapter 3. Given a constructed satio-temporal region, to make it safe, we should exclude from it the trajectories that will maintain the initial conflict and the ones that can induce a new conflict. As illustrated by Fig. 6.1, this means that we need to modify the inner border of the region (which was the initial trajectory of the aircraft) and its outer region.

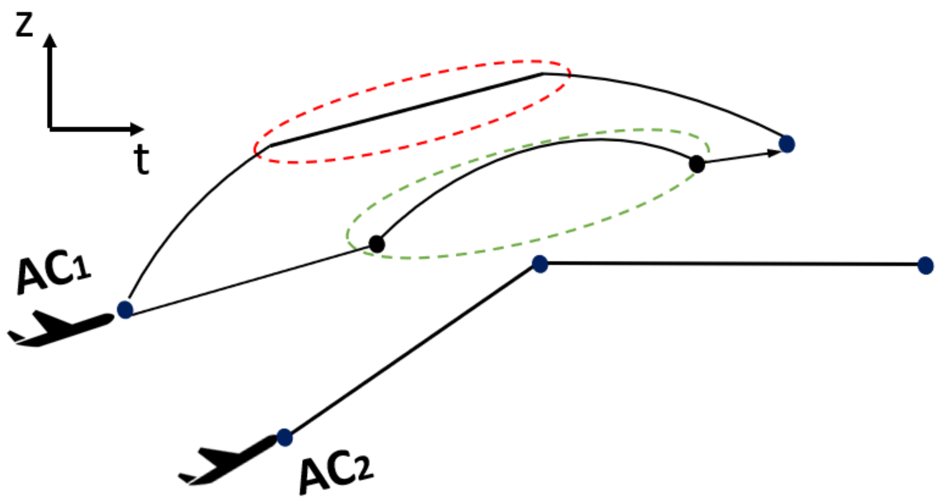


Figure 6.1: An example of modifying the inner border (within the green circle) and the outer one (within the red circle).

6.1.1 Modifying the Parabolic Regions

Modifying the Inner Border

Given that, the other aircraft has not maneuvered to solve the conflict on its own, to be free of conflict the inner boundary cannot be the original 4D trajectory of the aircraft. At the same time we want to provide the possibility to construct solutions with as small deviation from the original trajectory as possible. To find a solution satisfying both criteria we propose to construct an inner parabola that avoids the conflict area, but does not affect the rest of the original trajectory. The idea is illustrated in Fig. 6.2. Since the conflict interval is known in advance, the inner parabola can be constructed in a way that its ending points have the same x, z and time components with the points on the original trajectory of the aircraft at the beginning and end of the conflict interval. The idea can as well be described mathematically. A planar region of the ownship AC_1 in global coordinates, during the conflict interval is expressed as:

$$\begin{cases} x_1 = x_1(t) \\ a_{y1l}y_1^2(t) + b_{y1l}y_1(t) + c_{y1l} \quad \leq y_1 \\ \qquad\qquad\qquad\qquad\qquad\qquad \leq a_{y1u}y^2(t) + b_{y1u}y(t) + c_{y1u} \\ z_1 = z_1(t) \end{cases} \tag{6.1}$$

where a_{yu}, b_{yu}, c_{yu} are the parameters that would describe the movement of the aircraft if its trajectory would have been the outer parabolic bound (i.e. the y components of the acceleration, the initial velocity and the initial position of

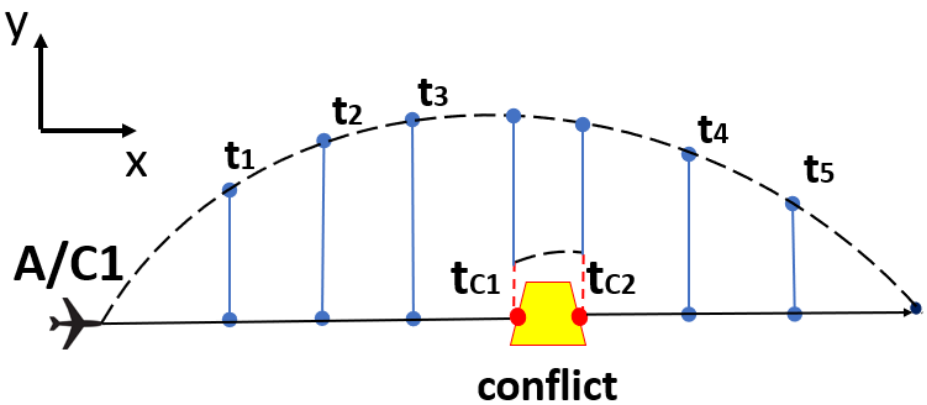


Figure 6.2: An example of a parabolic region. Since its inner border is already modified, the region maintains separation minimum with the other conflict aircraft

the aircraft), and a_{yl}, b_{yl}, c_{yl} are are the parameters that would describe the movement of the aircraft if its trajectory would have been the inner parabolic bound.
Similarly, the region of the intruder can be expressed as well:

$$\begin{cases} a_{x2l}x_2^2(t) + b_{x2l}x_2(t) & +c_{x2l} \leq x_2 \\ & \leq a_{x2u}x_2^2(t) + b_{x2u}x_2(t) + c_{x2u} \\ a_{y2l}y_2^2(t) + b_{y2l}y_2(t) & +c_{y2l} \leq y_2 \\ & \leq a_{y2u}y_2^2(t) + b_{y2u}y_2(t) + c_{y2u} \\ z_2 = z_2(t) \end{cases} \tag{6.2}$$

Construction of inner parabola The construction of the inner parabola has the sole purpose of avoiding the original conflict. This implies that its parameters depend only on the trajectory of the intruder (i.e. the other conflict aircraft) during the conflict time interval.
More precisely, the inner parabola of the onwship has the shape:

$$p_1(t) = \begin{bmatrix} v_{1x}t + x_1 \\ a_{1i}t^2 + b_{1i}t + c_{1i} \\ v_{1z}t + z_1 \end{bmatrix} \tag{6.3}$$

while the trajectory of the intruder during that interval:

$$p_2(t) = \begin{bmatrix} v_{2x}t + x_2 \\ v_{2y}t + y_2 \\ v_{2z}t + z_2 \end{bmatrix} \tag{6.4}$$

Having a conflict defined as in Eq. 3.2 and since we are considering only planar solutions, our goal is to find values for the parabola parameters such that:

$$d_p(p_1(t), p_2(t)) \geq H \tag{6.5}$$

In doing so, we want to deviate the least possible from the original trajectory. This can be interpreted as minimizing the distance of the further point of the inner parabola from the original trajectory.
Finding the inner parabola's parameters therefore translates into a minimization problem:

$$\begin{aligned} & \underset{a_{1i}, b_{1i}, c_{1i}}{\text{minimize}} & & a_{1i} t_f^2 + b_{1i} t_f + c_{1i} \\ & \text{subject to} & & d_H(p_1(t), p_2(t)) >= H, \forall t \in [t_{c0}, t_{c_1}] \end{aligned} \tag{6.6}$$

where t_f is the time at which the parabola has its bigger distance from the original trajectory, t_{c0} is the beginning time of the conflict interval, t_{c1} the final time of the conflict interval, and d_H is the 2D Euclidean distance.
The inequality of the problem is equivalent to an inequality with polynomial of the forth order with respect to time with form:

$$\alpha_0 t^4 + \alpha_1 t^3 + \alpha_2 t^2 + \alpha_3 t + \alpha_4 <= 0, \forall t \in [t_{c0}, t_{c_1}] \tag{6.7}$$

where $\alpha_0 <= 0$. This makes our expression further equivalent to:

$$\alpha_0 t^4 + \alpha_1 t^3 + \alpha_2 t^2 + \alpha_3 t + \alpha_4 <= 0, \forall t \in \mathcal{T} \tag{6.8}$$

where $\mathcal{T} := \{t_{c0}, t_{c_1}\} \cup ([t_{c0}, t_{c_1}] \cap \{t \in \mathcal{R} : 4\alpha_0 t^3 + 3\alpha_1 t^2 + 2\alpha_2 t + \alpha_3 = 0\})$, or in plain English t_{c0}, t_{c_1} and all the peaks of the forth order polynomial (max 3 of them). The reason we need to consider t_{c0}, t_{c_1} is because it can happen that all three stationary points of the polynomial to have negative values, yet the borders to have positive values, as illustrated in Fig. 6.3.

This means that our problem is transformed to a minimization problem with polynomial constrains with a minimum of two and a maximum of five constrains:

$$\begin{aligned} & \underset{a_{1i}, b_{1i}, c_{1i}}{\text{minimize}} & & a_{1i} t_f^2 + b_{1i} t_f + c_{1i} \\ & \text{subject to} & & f_t(a_{1i}, b_{1i}, c_{1i}) <= 0, \forall t \in \mathcal{T} \end{aligned} \tag{6.9}$$

The problem can be solved in this form or simplified by some extra constraint to the shape of parabola, specifically:

- The distance from the original trajectory at t_{c0} and t_{c1} to be equal;

This requirement can be expressed as:

$$a_{1i} t_{c0}^2 + b_{1i} t_{c0} = a_{1i} t_{c1}^2 + b_{1i} t_{c1} \tag{6.10}$$

by which we can express the value of a_{1i}, using the value of b_{1i} and leave the minimization problem with the form:

$$\begin{aligned} & \underset{c_{1i}}{\text{minimize}} & & a_{1i} t_f^2 + b_{1i} t_f + c_{1i} \\ & \text{subject to} & & g_t(b_{1i}, c_{1i}) <= 0, \forall t \in \mathcal{T} \end{aligned} \tag{6.11}$$

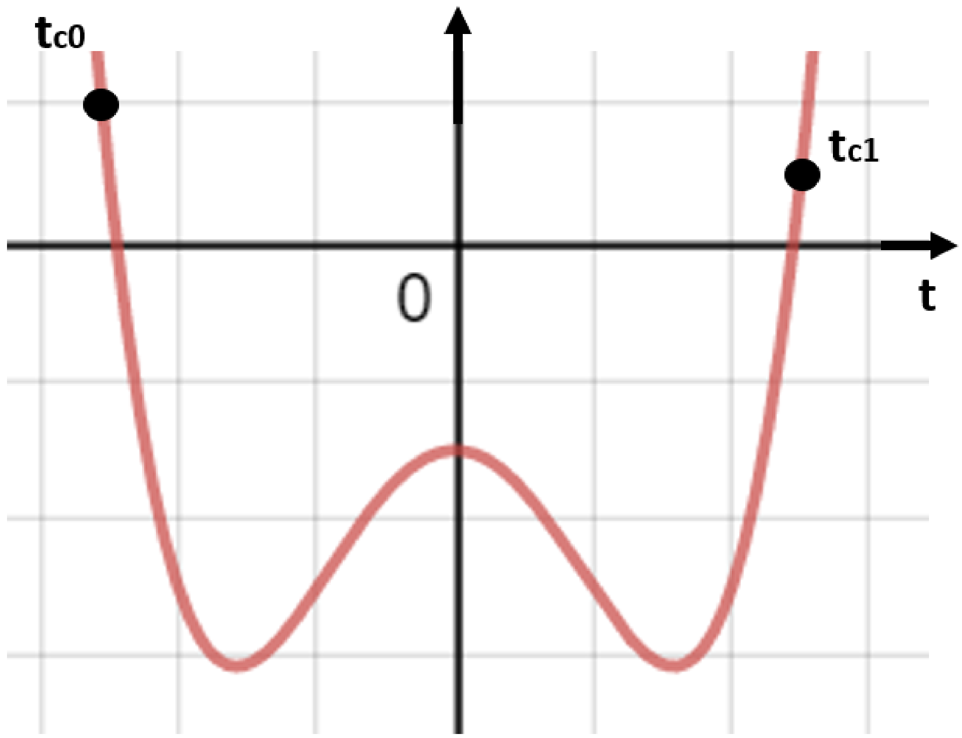


Figure 6.3: Illustration of the case when all three stationary points of a 4^{th} degree polynomial have negative values, while the points t_{c0} and t_{c_1} have positive values.

Modifying the Outer Border

The outer border of the region should be far enough to provide space for the construction of the inner border and eventually the new trajectory segments, but also close enough to fit the physical limitations of the aircraft and to avoid inducing new conflicts.
To satisfy the former two constrains, the outer coefficients of the region are chosen respecting the maximal values of the physical parameters of the aircraft (heading, acceleration, etc.). To provide a region free of conflict some checks, and in certain cases, some modifications of the region should be performed. More clearly, in a scenario where a potential regional induced conflict is detected, the conflict interval is identified and the ownship cuts linearly its outer region to preserve safety distance during that time window, as illustrated in Fig. 6.5. Fig. 6.6 illustrates a case where the required outer cut and the constructed inner parabola result in a safe space, where no possible safe trajectory can be constructed.

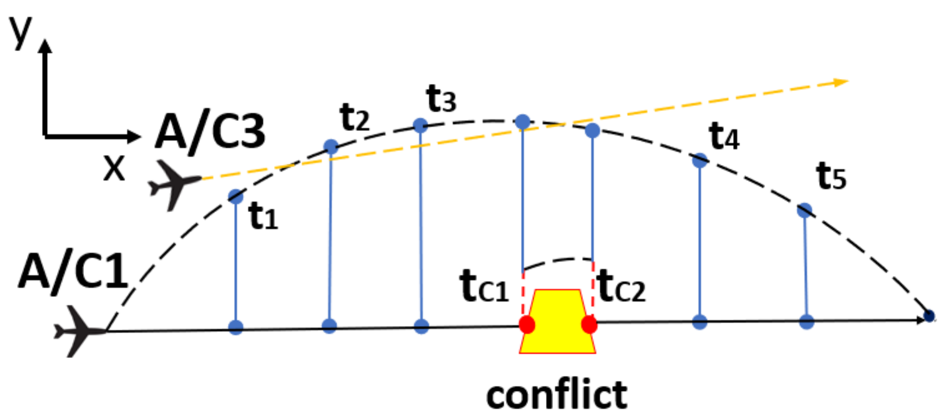


Figure 6.4: Illustration of scenarios when outer region needs to be modified to avoid possible induced conflict

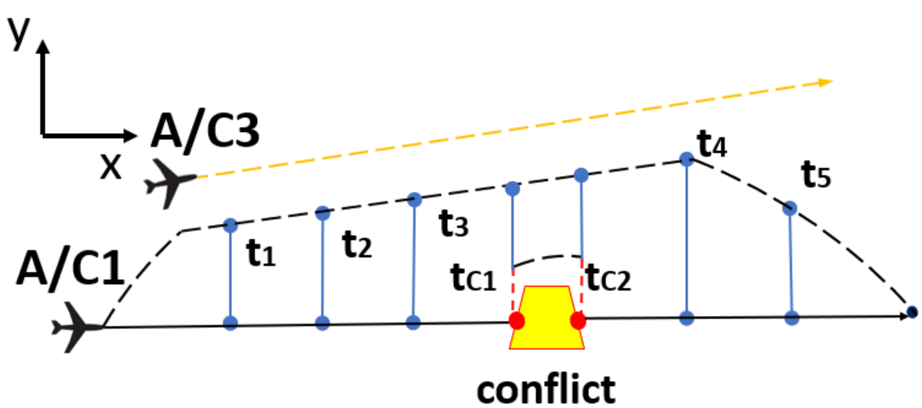


Figure 6.5: Case when the modification of the inner and outer border still provides feasible conflict-free trajectories

In the case when the surrounding aircraft is changing its flight level, it can happen that the conflict part of the region is within the region of AC_1, as illustrated in Fig. 6.7. In such cases, the proposed outer cut proposed is not efficient, since it can cut away significant conflict-free parts of the region. Moreover, this can result in non-feasible regions, where the outer and inner cut collide. In order to deal with such cases, a more refined outer cut needs to be introduced. Such cut splits the region in several parts, discards the conflicting ones and keeps the several conflict-free parts.

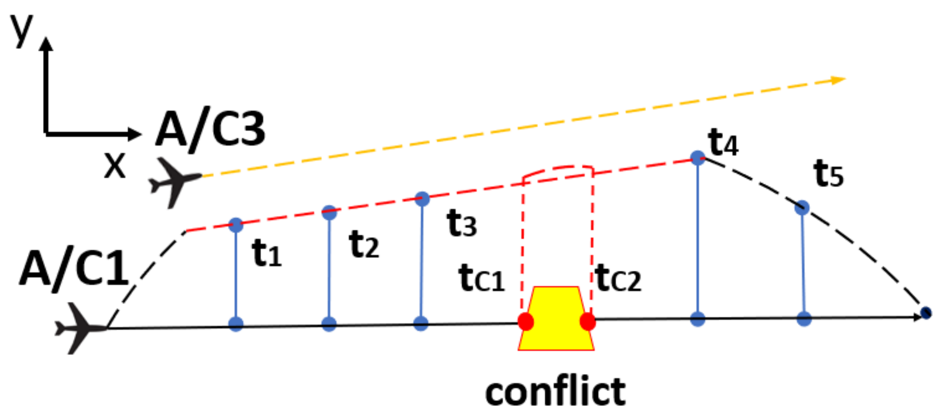


Figure 6.6: Case when the modification of the inner and outer border does not provides feasible conflict-free trajectories

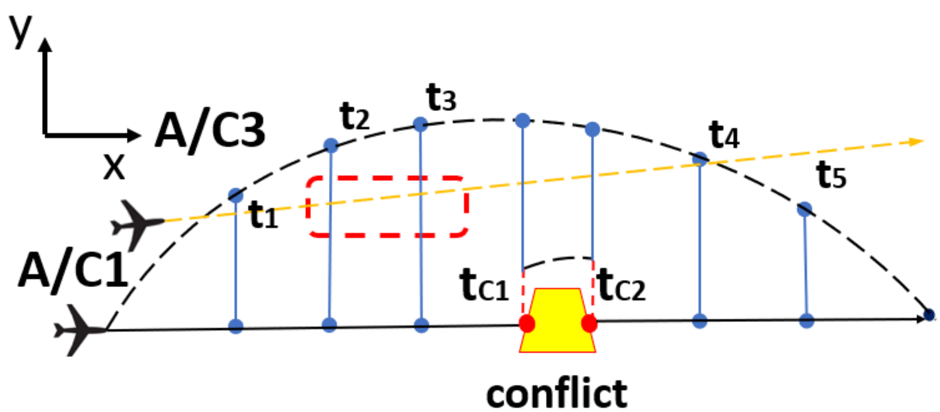
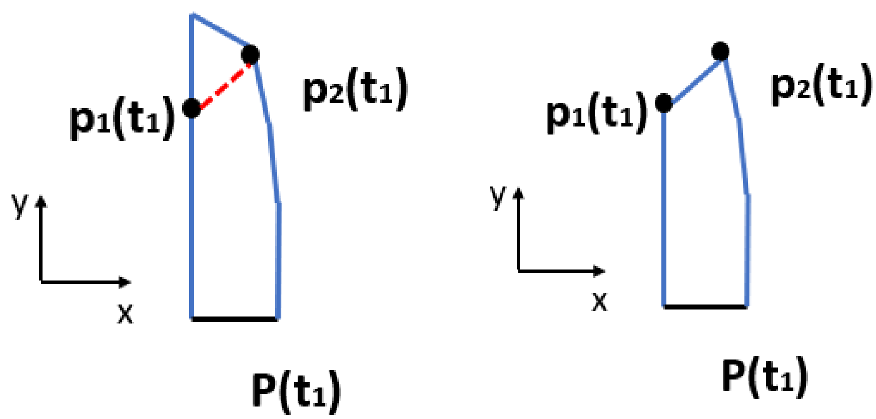


Figure 6.7: Case when the conflict part of the region lies totally within it

Modifying the Parabolic Regions by a Recurrent Cut

An alternative to the described cuts is the recurrent cut. It is more computationally expensive than the provided outer cut, however it uses space more efficiently (smaller parts of the regions are cut away). At the same time is less computationally expensive than then the provided inner cut, however, it can be slightly less efficient. It is essentially a special case of the recurrent cut presented in subsection 6.1.2, and therefore its details are explained there.



(a) The region before the cut

(b) The region after the cut

Figure 6.8: Example of a region before and after it is linearly cut.

6.1.2 Modifying the Heading-Based Regions

In the case of heading-based regions, instead of moving segments, we have to deal with moving polygons. There are two ways through which both inner and outer borders can be modified in this case, by a linear cut, or by a recurrent cut. Linear cut comes at a lower computational cost, but they cut away bigger portions of useful space.
Let $\partial P(t)$ be the boundary of $P(t)$, $\partial P_c(t)$ the part of the boundary that is involved in a conflict during the time interval $[t_s, t_e]$, and $\partial P_f(t)$ the part of the bound that is conflict-free. Let $e_1(t), e_2(t)$ be the two endpoints of $\partial P_c(t)$.

Modifying the Border by a Linear Cut

A linear cut is applied on the boundary of the moving polygon during a specified time interval. To perform a linear cut on $\partial P(t)$, during the time interval $[t_1, t_2]$, means to replace $\partial P_c(t)$ by the moving segment $[e_1(t), e_2(t)]$. An illustration is provided in Fig. 6.8. Note that the regions have a spatial component and a temporal one. Therefore, the presented regions, based on heading changes, are 3D bodies (they extend in x, y and t, but not in z) in a 4D space. However, the provided illustrations are screenshots, i.e. they represent the shape of the region in space at a given instance in time. The pseudo-code of linear cut is presented in algorithm 1. There, $ac_i \perp\!\!\!\perp_{r_i,r_j} ac_j$ stands for ac_i and ac_j being dependent when their regions of choice are respectively r_i and r_j.

Algorithm 1 Linear Cut Algorithm

$ac_i \leftarrow$ the aircraft of choice
$r_i \leftarrow ac_i$'s region that needs to be cut
$D \leftarrow \{ac_j | ac_i \perp\!\!\!\perp_{r_i,r_j} ac_j\}$
Identify, using D, the set of time intervals T, during which a cut needs to be performed
$\{\partial P_k(t)\}_{k=1}^{m_\tau} \leftarrow$ the set of non-overlapping border parts that need to be cut during the time interval τ
for all $\tau \in T$ **do**
  for all $\partial P_c(t) \in \{\partial P_k(t)\}_{k=1}^{m_\tau}$ **do**
    $(e_1(t), e_2(t)) \leftarrow$ the endpoints of $\partial P_c(t)$
    In r_i replace $\partial P_c(t)$ by $[e_1(t), e_2(t)]$
    if conflict not removed **then**
      terminate with no success
    end if
  end for
end for

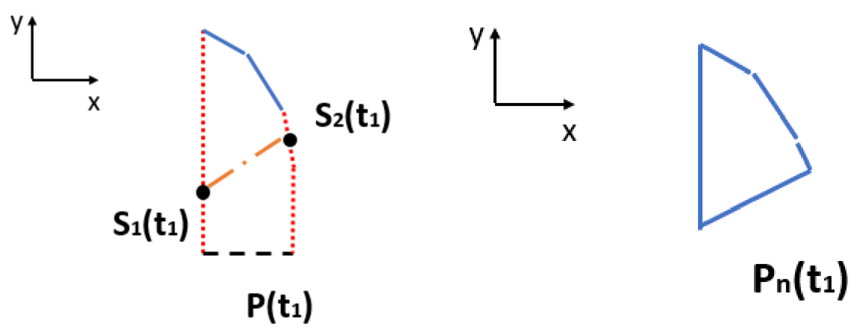
Modifying the Border through a Recurrent Cut

To perform on the other hand a recurrent binary cut, we proceed as follows: Let $S_{e1}(t), S_{e2}(t) \in \partial P_c(t)$ be the two end-segments involved in the conflict. In each of $S_{e1}(t), S_{e2}(t)$, we apply a recurrent, binary cut, based on the binary search principle [103]. This is done in order to obtain the longest possible conflict-free segment that is connected with the rest of $\partial P_f(t)$. Let $o_1(t)$ and $o_2(s)$ be the two obtained moving points. In case $[o_1(t), o_2(s)]$ is conflict-free, we modify the region r_i during $[t_s, t_e]$, such that its border is $\partial P(t) := \partial P_f(t) \cup [e_1(t), o_1(s)] \cup [o_1(t), o_2(s)] \cup [o_2(t), e_2(s)]$. If alternatively $[o_1(t), o_2(s)]$ is not conflict-free, we continue cutting $S_{e1}(t)$ and $S_{e2}(t)$ until the obtained points form a conflict-free segment. In the worst case scenario, we would have to cut away the whole $S_s(t)$ and $S_e(t)$ as in a linear cut. The pseudo-code of the recurrent binary cut is presented in algorithm 2.
The procedure is illustrated in Fig. 6.9. Black, dashed line represent the part of the boundary that is part of the original trajectory of the aircraft. Red, dotted lines present the part of the boundary in conflict and not part of the original trajectory. Blue, continues lines represent the conflict-free part of the boundary. Orange dotted and dashed line represent the new, conflict-free moving segment that is going to be part of the cut boundary.

6.1.3 Computational Complexity Considerations

Computational Complexity of Modifying the Parabolic Region's Borders

The inner bound of the parabolic region The construction of a safe inner bound is transformed into a minimization problem with a 4 dimensional



(a) The region after the cutting points have been decided.

(b) The obtained, conflict-free region.

Figure 6.9: Illustration of a recurrent, binary cut.

Algorithm 2 Recurrent, Binary Cut Algorithm

$ac_i \leftarrow$ the aircraft of choice
$r_i \leftarrow ac_i$'s region that needs to be cut
$D \leftarrow \{ac_j | ac_i \perp\!\!\!\perp_{r_i, r_j} ac_j\}$
Identify, using D, the set of time intervals T, during which a cut needs to be performed
$\{\partial P_k(t)\}_{k=1}^{m_\tau} \leftarrow$ the set of non-overlapping border parts that need to be cut during the time interval τ
for all $\tau \in T$ **do**
  for all $\partial P_c(t) \in \{\partial P_k(t)\}_{k=1}^{m_\tau}$ **do**
    $S_{c1}(t), S_{c2}(t) \leftarrow$ the end-segments of $\partial P_c(t)$
    Perform a recurrent binary cut on $S_{c1}(t)$ until it is conflict-free
    Perform a recurrent binary cut on $S_{c2}(t)$ until it is conflict-free
    $(o_{i1}(t), o_{i2}(t)) \leftarrow$ the two obtained endpoints from cutting $S_{c1}(t)$ and $S_{c2}(t)$ respectively
    if $[o_{i1}(t), o_{i2}(t)]$ is conflict-free **then**
      terminate with success
    else
      while $[o_{i1}(t), o_{i2}(t)]$ is not conflict-free **do**
        Cut out a small chunk of S_{c1} and S_{c2}
      end while
    end if
  end for
end for

---

variable in the case when we want both conflict aircraft to maneuver, or a 2 dimensional variable in the case when only 1 aircraft will maneuver to solve the pairwise conflict. Thus, the dimensionality of the problem is drastically decreased, compared to the state of the art, and does not depend on the total number of involved aircraft.
We would like to clarify further that the computational complexity does not change whether one or two aircraft are to maneuver. As mentioned in the paragraph above, regarding the outer bound, cases where two aircraft can maneuver can be handled by the methodology.

The outer bound of the parabolic region It is initialized as a parabola the coefficients of which are defined using aircraft's physical limitations. Then if necessary, i.e. if there potential conflicts[1] with the surrounding traffic, linear cuts are performed using the time-stamps obtained by the new potential conflict time interval. To compute a conflict interval, as explained earlier we need to solve 4 polynomial equations of the 4 order. This process can be done analytically and has *O(c)*, where c is a constant. The performance of the cut has also *O(c)* since all we do is calculate the coefficients of a line that passes through 2 points.
To construct the safe region of an aircraft that needs to maneuver, given the number of dependent aircraft is n and the number of its possible regions is m, ***the worst case*** scenario will have complexity *O(nm)* and in a distributed system the complexity of ***the worst case*** of constructing all the necessary safe regions is $O(n_{max}m_{max})$, where n_{max} is maximum number of dependent aircraft from a single aircraft that needs to maneuver and m_{max} is the maximum number of regions that an aircraft will claim to construct.

Computational Complexity of Cutting Moving Polygons

The complexity of linear cut is $O(c)$, where c is a constant. The recurrent cut's complexity depends on the length of the segment we are cutting. Specifically, let the length of the segment we want to cut be l and the length of the smallest piece we would consider be u, then the complexity of the recurrent cut is $O(log(l/u))$.

6.2 Conflict Resolution Maneuvering One Aircraft Based on Spatio-Temporal Regions

Algorithm 3 describes the proposed procedure. We assume that detected conflicts are pairwise and isolated. By "isolated" here we mean that no compound ecosystems exist. As soon as a conflict is detected, the corresponding ecosystem is identified. Since we are seeking for resolutions where only one aircraft needs to maneuver, the depth of the ecosystem can be restricted to two. So the

[1] By "conflict" here we mean a "conflict between parabolic regions", defined in the paper in section **IV. THE PARABOLAS EXAMPLE**, subsection **A. Conflict between parabolic regions**.

conflict aircraft (first order members) and the aircraft that are interdependent with them. After this, we need to decide which of the two conflict aircraft will maneuver. This decision is taken by a third entity, which can be a human ATCo, or an automated decision maker. In an informed environment, such a decision should be based on the impact that each aircraft can have on the rest of the airspace. Alternatively, heuristics can be used to take such a decision. As soon as the aircraft is chosen, a safe regions needs to be constructed.

Algorithm 3 CR using a Single Aircraft

```
Detect a Conflict.
Identify the corresponding ecosystem.
repeat
    Choose an aircraft to maneuver.
until A safe region is constructed, or no more candidate regions exist.
```

6.3 Conflict Resolution - Case Studies

In this subsection we present some results from applying the algorithm that utilizes the costructed parabolic regions to historical data from the DDR2 depository of EUROCONTROL. In order to get more conflicts, the planned traffic was utilized. The choice of which aircraft to maneuver was done at random. The chosen aircraft tries to construct a safe region and in case it fails, the other aircraft tries to do so.
The first scenario is composed of two aircraft, in conflict with each other. Their intervals (start and final point) are given in Table 6.1. Fig. 6.10 depicts the original geometry, in Fig. 6.11a the constructed safe region and the applied solution in Fig. 6.11b. Although the deviation looks significant in the picture, the actual extra traveled distance for AC_1 is 0.46647 NM as seen in Table 6.2.

Table 6.1: First and final point of each of the two aircraft in the first scenario

	x (NM)	*y (NM)*	*z (feet)*	*t*
AC_1 **(start point)**	0	0	22564	0
(final point)	34.5498	20.0301	31486	329
AC_2 **(start point)**	40.5246	33.4480	37000	0
(final point)	20.6444	1.0323	24697	329

In the second scenario a third aircraft is added to the two presented ones, as illustrated in Fig. 6.12a. The third aircraft, with starting and ending points presented in Table 6.3, is not in conflict with any of the other two over their

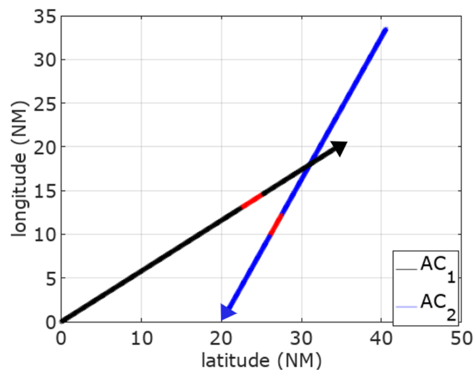
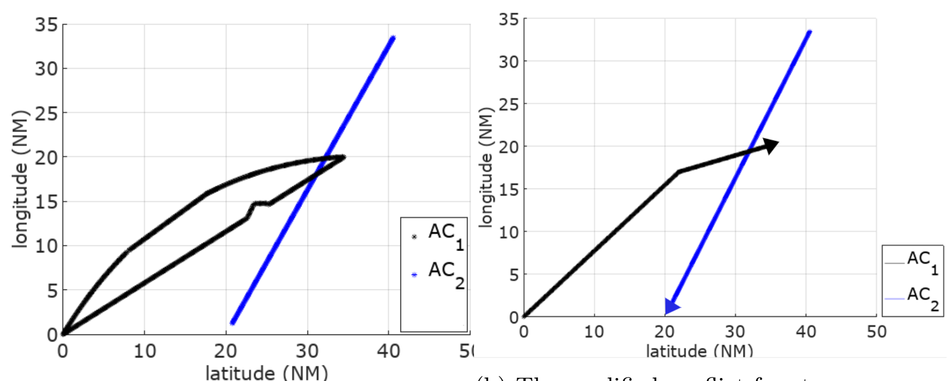


Figure 6.10: Scenario 1 - Original geometry with conflict



(a) The safe region to solve the conflict

(b) The modified conflict-free trajectory

Figure 6.11: Scenario 1 - AC_1's safe region and modified trajectory.

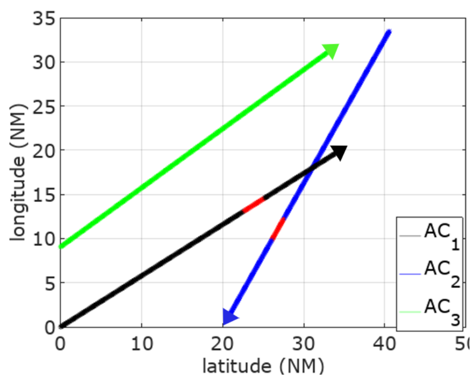
Table 6.2: Extra traveled distance for each of the two aircraft in the first scenario

	extra travelled distance *(NM)*
AC_1	0.46647
AC_2	0

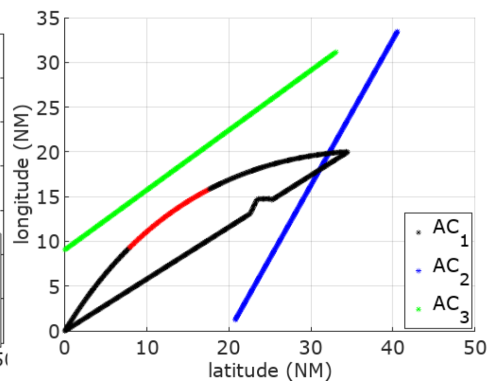
original trajectories, but as AC_1 constructs its region, a potential conflict with AC_3 appears as illustrated in Fig. 6.12b. This makes the construction of a safe region with an outer parabolic region impossible. However, an introduced linear modification not only fixes the problem, as illustrated in Fig. 6.13a, but also allows AC_1 to construct again the same trajectory as before (Fig. 6.13b). Table 6.4 confirms that the extra traveled distances remain the same.

Table 6.3: First and final point of each of the three aircraft in the second scenario

	x (NM)	*y (NM)*	*z (feet)*	*t (s)*
AC_1 **(start point)**	0	0	22564	0
(final point)	34.5498	20.0301	31486	329
AC_2 **(start point)**	40.5246	33.4480	37000	0
(final point)	20.6444	1.0323	24697	329
AC_3 **(start point)**	0	9.0669	28000	0
(final point)	33.2690	31.306	29000	329



(a) Original geometry with conflict



(b) AC_1 constructs a region which is not safe

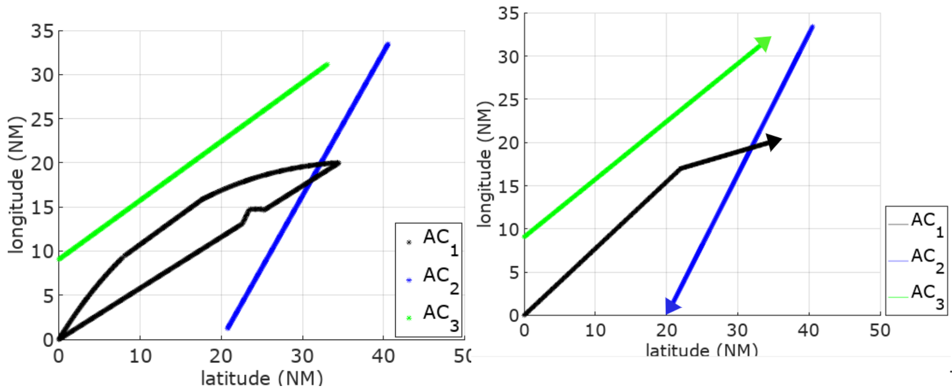
Figure 6.12: Scenario 2.

Table 6.4: Extra traveled distance for each of the three aircraft in the second scenario

	extra travelled distance *(NM)*
AC_1	0.46647
AC_2	0
AC_3	0

6.3.1 Resilience Discussion of Ecosystem 2

In Chapter 3, we defined the bottleneck of spatio-temporal regions as a quantification of their resilience. We introduce here uncertainties on AC_2 speed, or position and illustrate how they can be absorbed by the constructed spatio-



(a) The safe region to solve the conflict

(b) The modified conflict-free trajectory

Figure 6.13: Scenario 1 - AC_1's safe region and modified trajectory.

temporal region of AC_1, without the necessity to reconsider surrounding traffic. This comes at the cost of decreasing the bottleneck of the region.
We considered the scenario where, after AC_1 has constructed its safe spatio-temporal region, some uncertainty affects AC_2 speed, position, or both. In this case, the inner border needs to be modified, however the outer one stays unaffected. We let the speed of AC_2 vary by $\pm 5\%$ and the position of AC_2 to have a deviation of up to $2NM$ from its original trajectory. In all the simulated cases the inner border of spatio-temporal region could be modified and a resolution could be found within it. In the original case, where the velocity and position of AC_2 are not modified, the bottleneck was $7.04NM$. Introducing the modifications the bottleneck shrank to $6.07NM$ in the worst case. So we lost 13.78% in terms of resilience.

Chapter 7

Supporting Tactical Conflict Resolution Between Aircraft Through Air Spatio-Temporal Region Negotiation

In this chapter we propose a negotiation framework through which configurations of safe spatio-temporal regions can be agreed between aircraft. This allows conflict resolutions where more than 2 aircraft can maneuver, which means that more conflict geometries can be handled and costs can be distributed among aircraft. The agreed safe spatio-temporal regions can be further used to construct deviated trajectories that will avoid the original conflict. This mechanism fulfills the desired attributes described in subsection 1.9.1. It allows involved aircraft to keep their preferences private, it generates sets of resolutions instead of unique resolving configurations, and it considers interdependencies with the surrounding traffic within the specified time window.

7.1 Enhancing a delegated aircraft pairwise conflict resolution framework by the identification of temporal fences

After we identify the relevant aircraft, we attempt to construct safe regions for the conflict aircraft. We further determine, for each of the safe regions, the latest possible maneuver and the corresponding 4D trajectory, when no uncertainties are present. The deadlock time is the latest time among all the calculated ones.

We present the pseudocode of the procedure in algorithm 4.

As soon as we remove the pairwise interdependencies of a region, we need to

Algorithm 4 Deadlock Algorithm

```
Determine relevant aircraft.
for all conflict aircraft do
  Determine safe regions.
end for
for all safe regions do
  Determine the latest possible safe trajectory and the corresponding time.
end for
Determine the latest possible option among safe regions.
```

construct within it, the latest possible safe trajectory. Constructing the latest possible safe trajectories for each obtained safe region, allows us to determine the latest maneuver time for each region, which we call the expiration time of the region. The deadlock time is the latest possible expiration time among all conflict-free regions, and the deadlock maneuver is the corresponding maneuver.

7.1.1 Complexity Considerations

As we explained in Chapter 6.1.3, the complexity of linear cut is $O(c)$, where c is a constant and the recurrent cut's complexity depends on the length of the segment we are cutting and reads $O(log(l/u))$ (the length of the segment we want to cut be l and the length of the smallest piece we would consider be u). To determine the latest possible maneuver, we are also using a binary search, but on the time dimension. Let dt be the duration of the segment we are considering, then the complexity of determining the latest possible maneuver is $O(log(dt))$. The complexity therefore of the deadlock algorithm is $O(m(log(l/u)+log(dt)))$, where m is the number of regions the aircraft is considering. Note that the algorithm's complexity is independent of the number of aircraft involved in the conflict resolution procedure.

7.2 Calculating Deadlock - Case Studies

In this section, we evaluate the method using historical traffic data from Eurocontrol's Demand Data Repository II (DDR II). We used data regarding planned trajectories from 12.02.2019. The altitudes of the aircraft are modified such that the highest flight level is 25000 feet. This is done with the purpose of detecting more conflict situations. Among the analyzed conflicts, we present three scenarios, one with a head on encounter and not surrounding traffic, another with a more "relaxed" conflict geometry and no surrounding traffic, and a last one that includes some surrounding traffic.

Conflicts are detected, as before, using the methodology proposed in [102] with an added filter to discard the false positive results. As soon as a conflict is detected, the originally planned trajectory of each involved aircraft is filtered from five minutes before entering the conflict interval until two minutes after exiting the conflict interval. The duration of the ecosystem is therefore seven minutes plus the duration of the conflict (of course, the used time windows are parameters that can be altered). A maximum deviation angle of 60 degrees is used to construct the aircraft's space-time regions. Three regions are build for each aircraft, region "left" bounded by aircraft's original trajectory and its leftmost trajectory that the aircraft can achieve given its configuration, region "right" bounded by aircraft's original trajectory and its rightmost trajectory it can achieve given its configuration, and region "straight" including only the original trajectory of the aircraft. Units are nautical miles for x and y, feet for z and seconds for time.

7.2.1 A head-on encounter scenario in a two-members ecosystem

The first scenario we present contains a conflict where the trajectories of the conflict aircraft form a 180 degrees angle between them, as shown in Fig. 7.1. AC_1's trajectory is the black one and AC_2's is the green one (a considerable part of the trajectories are overlapping). The red segment is the part of their trajectories during which a loss of minimum separation occurs. Table 7.1 contains the 4D points of each aircraft. We have a head-on conflict and in case it is not solved a collision is possible, therefore the situation is of high criticality.

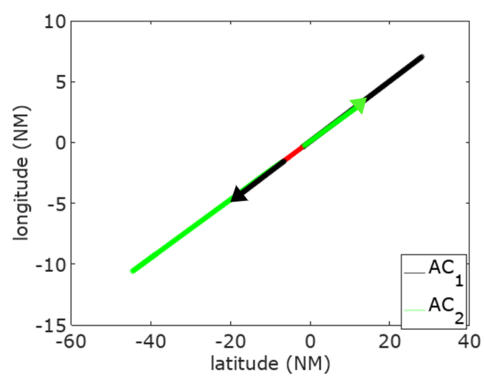
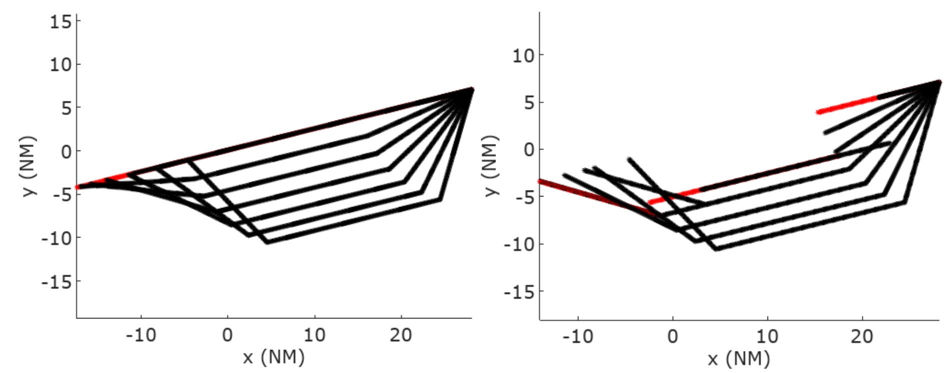


Figure 7.1: Conflict geometry for scenario 1.

The geometry of the conflict creates a symmetric situation, where maneuvering AC_1, or AC_2, on left, or right have the same latest possible time to maneuver. Fig. 7.2 illustrates the left region of AC_1 before and after the necessary recurrent cut is performed.
In Fig. 7.2b we depict how the border points of the region evolve over time. The red trajectory is the trajectory of the first point of the region. As can be seen there, after performing the cut on the middle section of the selected region, the

Table 7.1: Original trajectories for the aircraft of scenario 1.

	x	y	z	t
AC_1	28.11	7.07	25000	0
	15.32	3.89	25000	120
	-4.63	-1.05	25000.0	307
	-17.43	-4.22	25000.0	427
AC_2	-44.64	-10.59	25000.0	0
	-28.73	-6.78	25000.0	120
	-3.94	-0.84	25000.0	307
	11.97	2.97	25000.0	427



(a) AC_1's left region before the cut.

(b) AC_1's left region after the cut.

Figure 7.2: AC_1's left region before and after the cut.

point in the initial, expanding section at which the latest possible, conflict-free maneuver can be performed, need to be calculated. This time results to 67 seconds after the beginning of the ecosystem.

The time from the beginning of the ecosystem until the beginning of the conflict is 5 minutes. Having a deadlock at 67 seconds after the beginning of the ecosystem means that only 22.3% of the time before the conflict can be used for a possible negotiation between the aircraft to reach a more efficient resolution.

7.2.2 A more "relaxed" scenario in a two-members ecosystem

We present as the second scenario a conflict which can be resolved by a single maneuver quite late. Fig. 7.3 illustrates the original geometry. As before, AC_1's trajectory is the black one and AC_2's is the green one. The red segment is the part of their trajectories during which a loss of minimum separation occurs. Table 7.2 contains the trajectory points for each of the two aircraft. In this case a loss of separation, under no wind uncertainties is unlikely to result in a physical collision and therefore we would expect a later last possible maneuver compared to scenario 1. In Fig. 7.4 we represent the region that contains the deadlock, before and after the cut.

The deadlock of this scenario is at 224 seconds after the initial point of the

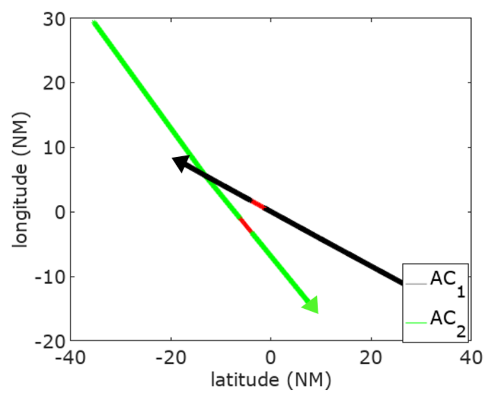
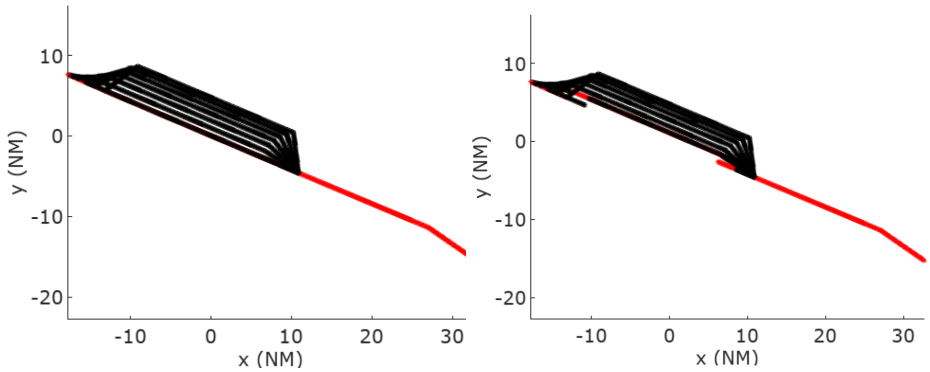


Figure 7.3: Conflict geometry for scenario 2.

Table 7.2: Original trajectories for the aircraft of scenario 1.

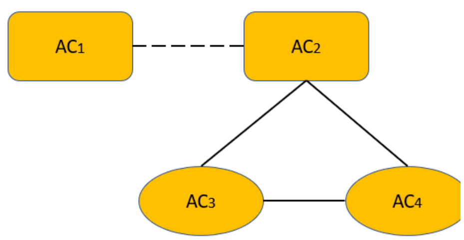
	x	y	z	t
AC_1	32.68	-15.28	25000.0	0
	27.07	-11.39	25000.0	56
	10.88	-4.59	25000.0	194
	6.24	-2.62	25000.0	234
	-13.15	5.61	25000.0	402
	-17.75	7.63	25000.0	442
AC_2	-35.33	29.32	25000.0	0
	-13.15	5.61	25000.0	231
	-10.83	3.41	25000.0	253
	5.61	-12.22	25000.0	416
	7.92	-14.43	25000.0	442

ecosystem. This means that 74.6% of the time before the conflict is available for aircraft to negotiate and try to agree a more efficient solution.

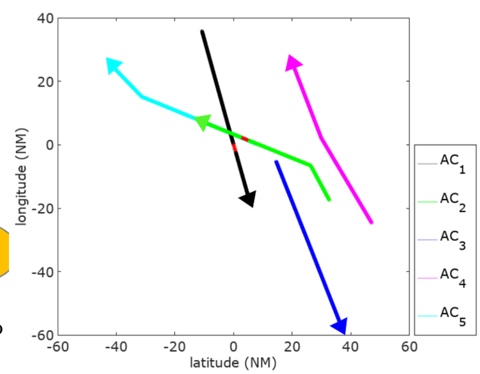


(a) AC_1's left region before the cut. (b) AC_1's left region after the cut.

Figure 7.4: AC_1's left region before and after the cut.



(a) Pairwise Interdependencies for scenario 3.



(b) Conflict geometry for scenario 3.

Figure 7.5: Conflict geometry and pairwise interdependencies for scenario 3.

7.2.3 A scenario with surrounding traffic

The third scenario we present, is one which includes surrounding traffic. There are two aircraft that are involved in the conflict and three more aircraft that second order members of the ecosystem. Fig. 7.5a represents the interdependencies graph of the ecosystem. Conflict aircraft are represented by yellow circles and surrounding traffic by black rectangles. In Fig. 7.5b we illustrate the ecosystem geometry before the resolution. AC_1's trajectory is the black one and AC_2's is the green one. The red segment is the part of their trajectories during which a loss of minimum separation occurs. The trajectories of the aircraft are given in Table 7.3.

In this scenario the deadlock is reached 202 seconds after the initial point of the ecosystem. This means that 67.3% of the time before the conflict occurs,

Table 7.3: Original trajectories for the aircraft of scenario 3.

	x	y	z	t
AC_1	-10.76	35.80	25000.0	0
	-9.77	32.45	25000.0	29
	-2.33	7.67	25000.0	235
	0.72	-2.29	25000.0	319
	5.05	-16.44	25000.0	439
AC_2	32.62	-17.42	25000.0	0
	26.28	-6.55	25000.0	107
	2.46	2.36	25000.0	319
	-11.00	7.40	25000.0	439
AC_3	14.53	-5.30	25000.0	0
	18.45	-14.43	25000.0	76
	24.08	-27.54	25000.0	183
	26.86	-34.02	25000.0	236
	29.79	-40.91	25000.0	293
	37.33	-58.61	25000.0	439
AC_4	47.09	-24.62	25000.0	0
	40.53	-14.41	25000.0	95
	35.49	-6.57	25000.0	170
	29.90	2.10	25000.0	250
	26.93	9.25	25000.0	308
	23.11	18.39	25000.0	383
	20.37	24.96	25000.0	439
AC_5	7.41	0.42	25000.0	0
	-4.98	5.14	25000.0	107
	-19.42	10.65	25000.0	232
	-31.29	15.13	25000.0	332
	-40.86	24.30	25000.0	439

can be used for negotiations.

7.3 The Proposed Automated Negotiation

Figure 7.6: The three functionalities of an agent.

In this section, we attempt to generate configurations of safe spatio-temporal regions by using automated negotiation. These regions can be further used to choose trajectories that will solve the given conflict. Automated negotiation, as explained in Chapter 2, is a mechanism with the aim of letting autonomous agents try and reach an agreement [104]. To be capable to participate in an automated negotiation process, an agent should be able to generate offers that could resolve the problem, to evaluate them, and exchange them with the other involved parties [105]. The three functions are illustrated in Fig. 7.6. To implement such a mechanism, we have to describe the domain of the potential solutions, within which agents will negotiate, the manner agents quantify their preference over the possible alternatives, the technique by which they generate new offers, and lastly the negotiation protocol that the agents need to follow in order to communicate and exchange offers.

7.3.1 The Domain

To avoid a conflict, at least one of the involved aircraft need to perform a maneuver. Such maneuvers can be simple, i.e. a heading alteration, a velocity module modification, or an altitude change, or compound, i.e. a combination of several simple maneuvers. The maneuvers used in this work are simple maneuvers.
If a heading alteration is performed, the aircraft need to perform a horizontal maneuver to initially deviate from the original trajectory and thereafter another horizontal maneuver to go back on track. An example is illustrated in Fig. 7.7. There, the continuous arrow represents the original trajectory of the aircraft, and the dashed segments represent a modified trajectory. Such a trajectory is generated through a left initial maneuver of the aircraft.
In Chapter 3 we propose a way to analytically represent the totality of trajectories generated through planar deviations. Such trajectories can be grouped in two spatio-temporal regions, LEFT and RIGHT. Region LEFT contains modified trajectories generated by an initial left deviation from the original trajectory. Region RIGHT contains modified trajectories generated by an initial right deviation from the original trajectory. The domain on which our aircraft/agents negotiate is made up of combinations of safe spatio-temporal regions for the involved aircraft.
To generate these regions for each aircraft, we use the three-step procedure,

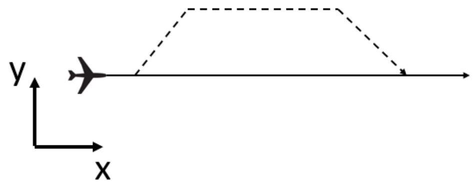


Figure 7.7: Example of an initial trajectory and a modified trajectory generated through a planar, left deviation.

Algorithm 5 Regions Generation Algorithm

```
Initialize regions LEFT and RIGHT.
for all Region r do
  Cut the part of r that might raise a conflict with a surrounding aircraft.
end for
for all Region r do
  Identify the part of r that is involved in the original conflict.
  Generate new regions by cutting progressively parts of the subregion being
  in conflict
end for
```

described by algorithm 5. Firstly, regions LEFT and RIGHT are initialized by the procedure described in Chapter 3. Secondly, for each of the two regions, using the information generated by the aerial ecosystem initialization, we cut the parts that might cause a loss of separation with some surrounding aircraft. In this way we can let only the conflict aircraft participate in the negotiation process and generate resolutions that resolve the initial conflict, while not inducing new ones. The obtained regions will contain trajectories that are either free of conflict, or in conflict with the original conflict aircraft. Thirdly, we identify the part of the new regions that are in conflict with some region of the other aircraft involved in the original conflict. We generate alternatives by cutting progressively larger parts of the conflict pieces. More specifically, the first alternative will contain the whole conflict portion of the region, i.e. nothing will be cut away. The last alternative will cut away the whole conflicting portion of the region. In this way it will contain trajectories that solve the conflict without the need for the other aircraft to maneuver. The rest of the alternatives are generated by cutting only part of the conflict portion of the region.

In Fig. 7.8 and Fig. 7.9 we illustrate the process. Fig. 7.8a represents the full initial region. The red triangle represents the part of the region that is involved in the conflict. The yellow rectangles represent areas that are interdependent with some surrounding aircraft. Therefore, if a trajectory is going to be constructed to pass through the yellow areas, it will solve the original conflict, but it will raise a new one. Fig. 7.8b represents the region after the yellow rectan-

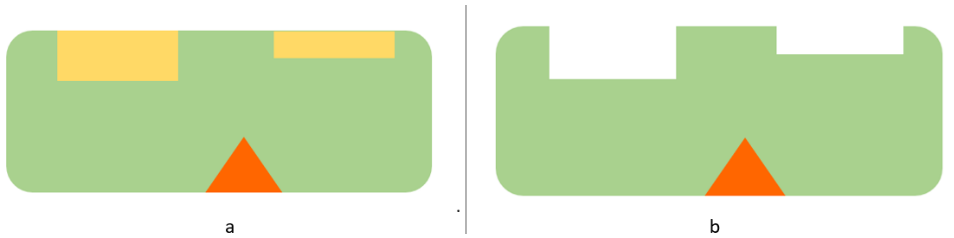


Figure 7.8: Toy diagram to illustrate cutting the part of the region interdependent to some surrounding traffic aircraft.

gles are cut away. In Fig. 7.9 various regions obtained after the third step is performed are illustrated. Fig. 7.9a contains the whole conflict triangle. In Fig. 7.9b a small part was cut away. Fig. 7.9c contains even a smaller part of the conflict triangle, while in Fig. 7.9d the whole conflict triangle is cut away.
Note that, the shapes used are not equivalent to the real shapes of the regions.

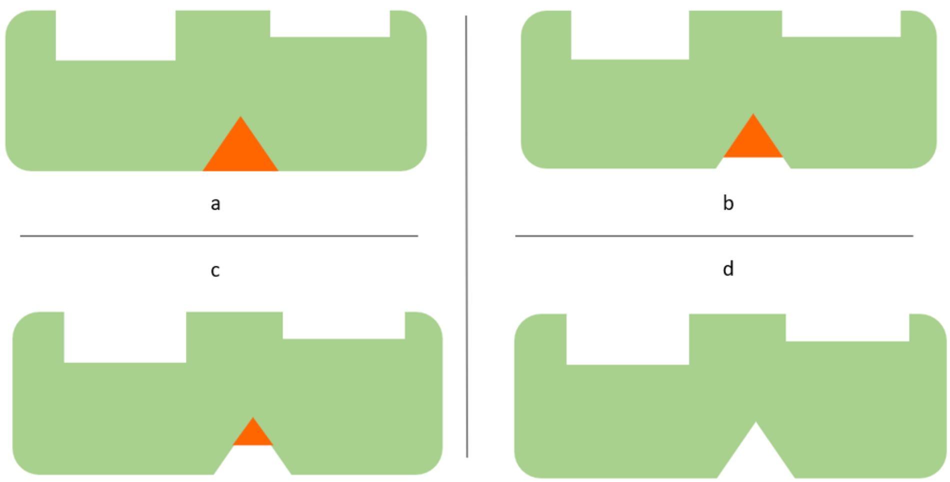


Figure 7.9: Toy diagram to illustrate cutting the part of the region interdependent to some surrounding traffic aircraft.

The real regions have three dimensions, i.e. the two planar dimensions (x and y) and time. The used figures are only to illustrate the process schematically. The domain is therefore made up from pairs of the generated regions (one region per each conflict aircraft), that are conflict-free between them.

7.3.2 Preference Elicitation

There are two ways that an individual agent can express preferences between two possible alternatives, qualitatively and quantitatively [106]. In qualitative approaches, each agent imposes a partial, or total order on the possible alternatives. Such an order lacks any numerical information, i.e. if an agent prefers alternative A over alternative B there is no way to measure how much more A is preferred over B. In quantitative approaches, a utility function is defined over alternatives. In this case we can express preference between two alternatives and be able to quantify this preference. In the aeronautical sector, each potential trajectory that an aircraft can follow, will result in a certain cost (in fuel and time). This cost can be measured, or estimated, thus a quantitative preference elicitation is possible. In general, ATCos prefer heading-based resolutions to speed-based ones and pilots prefer heading-based resolutions to altitude-based ones. Given in our domain we used only heading-based regions, we do not face such problems.

We assume that the original trajectory of each aircraft is the optimal one[1]. A potential deviation will therefore result in some cost in fuel and some delay. To quantify such costs, Pritchett and Genton [31] use a function of the following form is used:

$$c = (1 - \alpha) * C_f * \Delta f + \alpha * C_t * \Delta t \tag{7.1}$$

where $\alpha \in [0, 1]$ is the normalized cost index, $(C_f * \Delta f)$ the cost of the additional fuel, and $C_t * \Delta t$ the cost of the additional time.

C_f and C_t depend on the type of the aircraft, while α depends on the company's current priorities (under different circumstances minimization of delays, or fuel costs could be of priority).

Delgado and Prats [107] use a slightly different formulation of the above function:

$$c = C_f * \Delta f + CI * C_t * \Delta t \tag{7.2}$$

where CI is the cost index of the aircraft.

Note that, while we use such cost functions, the methodology is independent of the form of the functions. An agent can use as its cost function, any function of the form $f : D \rightarrow \mathbb{R}$.

In our formulation, agents are negotiating regions, i.e. sets of an infinite number of possible trajectories. As the cost value of a region, we decided to make use of the cost of a trajectory within this region, specifically the modified trajectory that has the minimum possible deviation from the original one. This choice is justified under lack of uncertainties, however, in more realistic scenarios were uncertainties are considered, in needs to be reexamined. This can be seen as an optimistic estimation of the costs, i.e. the involved aircraft are expecting to reach a consensus early enough, so they can intent to follow the trajectory that introduces minimal deviations.

7.3.3 Generating & Accepting Offers

Having the set of potential alternatives and a way to evaluate them, an agent needs a technique to generate potential offers. Our system is a time-critical

[1]This assumption is in compliance with the Direct Routing concept.

system, therefore a non efficient solution is preferred over no solution at all. This suggests that, given there is enough time, an agent can seek to achieve an efficient solution for itself. Yet, if the time is scarce, a solution that is not necessarily efficient should be accepted. In other words, a time-dependent technique of generating and accepting offers is adequate.
Faratin et al. [93] present several families of agents' "negotiation tactics", among which, the family of time dependent negotiation tactics. Given that each agent chooses an initial offer and its reservation value[2], through a time dependent behavior it is suggested to offer at the beginning of the negotiation the initial value and at the end of it the reservation value. Moreover, the more adequate alternative to offer at each time step is described through a continuous function that maps time to desired costs values. In systems where an agent tries to minimize costs, such a function would be monotonically increasing[3]. We adapt and use such functions to generate the desirable cost value at each time step. Among the alternatives that offer this cost, our agents choose randomly which one to offer. Moreover, this cost value is used to evaluate the offers that the other party is providing. If such an offer comes at a cost lower than its desirable one, the agent accepts the offer and the negotiation procedure is terminated with success.

7.3.4 The Negotiation Protocol

A negotiation protocol is the set of rules that describe the interaction of the negotiating parties, and their possible actions. We use the so called "alternating offers protocol" [108], which is a protocol that allows two involved agents to negotiate. One agent has to initiate the negotiation by generating an offer and sending it to the other party. At the reception of the offer, the other party can accept, or propose a counter-offer. The procedure goes on until an agreement is reached, or the negotiation time limit is reached.
Note that while the protocol is pairwise, it can be extended and used in negotiation between more parties, as discussed in sections 2.2 and 8.2.

7.3.5 Calculating the Deadline of the Negotiation

We use as the deadline of the negotiation, the deadlock calculated using the procedure proposed in section 7.1. There we identified the latest possible resolution that can be performed by maneuvering a single aircraft. Consideration of resolutions where more aircraft can move, would generally lead to a latest deadlock. However, in the performed simulations, we used the single aircraft deadlock. This, as illustrated later, by the simulation results had little impact

[2] The reservation value of an agent, is the offer of the highest individual cost that the agent is willing to pay to reach an agreement.

[3] This in case the utility functions represent a cost that we are trying to minimize. In case the utility function represents a profit, then the behavior function should be monotonically decreasing

on the negotiation procedure, given that agreements were reached in less than 500 milliseconds.

7.4 Automated Negotiation Simulation Results

7.4.1 Data and the Used Parameters

We evaluate the method using traffic data from Eurocontrol's Demand Data Repository II (DDR II). Specifically, a file containing the daily traffic of 12.02.2019 over London TMA area, i.e. aircraft flying between 51.01 and 52.05 degrees of latitude, -0.85 and -0.14 degrees of longitude. We impose as well as minimum flight level 245 (i.e. above 24500 feet).
The used minimum horizontal separation is 5 nautical miles (NM) and the minimum vertical separation is 1000 feet (ft). Conflicts are detected using a methodology based on the proposal in [102]. As soon as a conflict is detected, the originally planned trajectory of each involved aircraft is filtered from five minutes before entering the conflict interval until two minutes after exiting the conflict interval. Hence, the total time length of the ecosystem is seven minutes plus the length of the conflict. Since we are seeking solutions where only the conflict aircraft are potentially deviating from their original trajectory, we extend ecosystems up to the second order. As defined and explained in section 4.3, this means that an aircraft AC_i is a member of a given ecosystem, only if one of the following statements is true:

- The aircraft AC_i is involved in the original conflict.
- There exist a potential maneuver, which one of the conflict aircraft AC_c can perform and will cause a new conflict between AC_i and AC_c. In this case, both the maneuver and the new conflict should happen during the time interval within which the ecosystem exists.
- There exist a combination of resolution maneuvers that AC_i and AC_c can perform that will cause a conflict between them. In this case also, the maneuvers and the new conflict should happen during the time interval within which the ecosystem exists.

A maximum deviation angle of 60 degrees is used to construct the aircraft's space-time initial regions. Three initial regions are built for each aircraft, region "left" bounded by aircraft's original trajectory and its leftmost trajectory that the aircraft can achieve, given its configuration, region "right" bounded by aircraft's original trajectory and its rightmost trajectory it can achieve given its configuration, and region straight including only the original trajectory of the aircraft. Subsequently, the parts of the regions causing an interdependency with some surrounding traffic aircraft are cut away to obtain the intermediate regions. At a third step, we generate the final regions, by cutting away pieces of the conflict part of the intermediate regions. We generate ten final regions from intermediate region "left", and ten final regions from intermediate region

"right". The fuel costs for each deviation are calculated using BADA 3.15, within BlueSky, an open source Air Traffic simulator [109].
Following, we use General Environment for Negotiation with Intelligent multi-purpose Usage Simulation (GENIUS) [110] as the simulation environment where we perform the simulated negotiations. GENIUS is an automated negotiation suite that is used in many applications, including the international Automated Negotiation Agents Competition (ANAC) [94]. We use two types of strategies to generate offers for each agent, a boulware and a conceder one. A boulware agent tends to seek a low cost solution until the negotiation time is almost over. On the contrary, a conceder agent relaxes its requirements earlier and is inclined to reach an agreement as early as possible. Each of the four possible strategies coupling models a different scenario. The case with two boulware agents, represents a situation where two aircraft of competing companies encounter each other. The case with two conceder agents represents a situation where two aircraft of the same company need to negotiate. The other two cases model scenarios in between. For each of the possible strategies coupling scenarios we have run one hundred simulations. As the reservation value of each agent we have chosen its feasible alternative with the highest possible cost.

7.4.2 Two representative ecosystems

In this subsections we present and discuss the results for two ecosystems. The first ecosystem consists of two members only, i.e. the two aircraft involved in the conflict. This means that their generated regions are not constrained by surrounding traffic. Fig. 7.10 illustrates the planar geometry of the original trajectories. The black trajectory is the trajectory of AC_1, and the green one is the trajectory of AC_2. The red segments are the parts of the trajectories involved in the conflict. To indicate the direction of the aircraft, an arrow is depicted at the end points of each trajectory.
In order to represent the domain of negotiation, the parameters of the equation

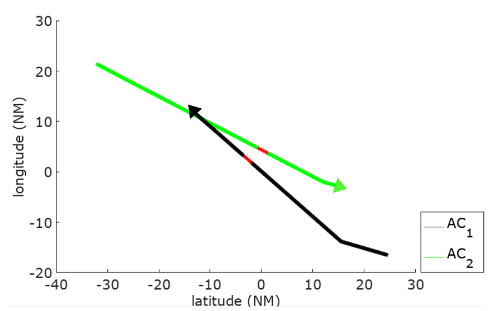


Figure 7.10: The original trajectories of the two aircraft of the first ecosystem in a planar projection.

7.1 need to be decided. In Fig. 7.11 we represent the domain for the case when

$\alpha = 1$, i.e. each aircraft's objective is to minimize its delays without being concerned about fuel consumption. In Fig. 7.12 on the other hand, we represent the domain when $\alpha = 0$, i.e. each aircraft is concerned to minimize fuel consumption, without considering delays. In both cases, we take $C_d = C_f = 1$. Since the two cases result in similar qualitative shapes of the domain, we will discuss here only the simulation performed for the case when both aircraft are concerned about their delays only.
The bottleneck of the regions in the domain was calculated to range from $26.59NM^2$ to $53.90NM^2$. Note that, the high value of the upper bound is a result of the fact that domain includes also regions that are cut minimally to handle the conflict. As an example, we can consider the bid $(12, 3)$ from Fig. 7.11. For that bid, AC_2's deviation is small, and therefore its corresponding region is minimally cut. This results in a high value of the bottleneck.
Fig. 7.13 presents the summary of the negotiation agreements in all of the run simulations with respect to the cost of the first aircraft and the second one. The blue circles represent results obtained while both agents were using a boulware strategy. The red ones represent results obtained while the AC_1 was using a conceder strategy, and AC_2 a boulware one. The green circles illustrate the results of the cases when AC_1 was a boulware and AC_2 a conceder. Finally purple circles illustrate results from scenarios when both agents were conceders. The radius of the circles is proportional to the number of simulations during which we obtained the corresponding result.

One criterion to judge the results is with respect to their distance from the

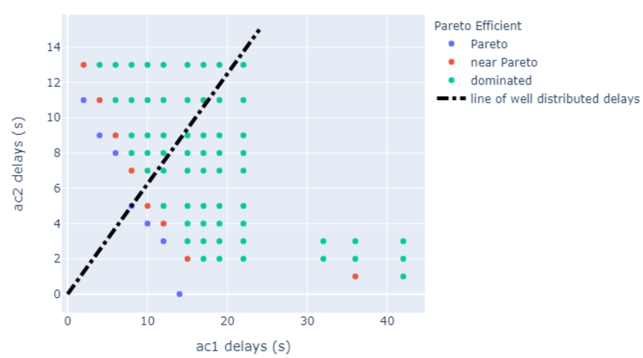


Figure 7.11: The possible bids if both aircraft consider only delays.

Pareto frontier. Another one is based on how well the costs are distributed between the two involved parties. Since the two parties have alternatives with different costs (the delays of AC_2 are generally smaller than the ones of AC_1 in the first ecosystem), we would judge the goodness of the delays distribution based on how far an alternative is from the line passing from the points

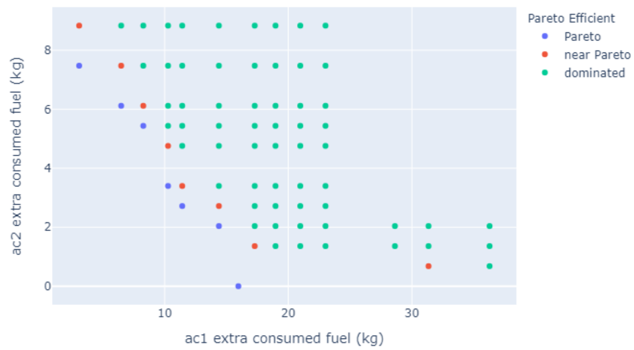


Figure 7.12: The possible bids if both aircraft consider only extra fuel costs.

ec1	***b-b***	***b-c***	***c-b***	***c-c***
Pareto	58%	74%	96%	52%
near Pareto	84%	91%	97%	82%
well distributed	93%	0%	0%	92%

Table 7.4: Results regarding efficiency of the resolutions and distribution of costs among aircraft for ecosystem 1.

$(0, 0)$ and $(8, 5)$ (which is the middle point of the Pareto frontier). Results are summarized in Table 7.4. As we can see, when two aircraft follow different strategies, the agreement tend to lie more often in the Pareto front. However, if we consider near optimal agreement also[4], the difference decreases significantly. On the other hand, if we consider cost distribution, the scenarios where both parties follow similar strategies outperform clearly the ones where the parties follow different strategies. In terms of time spent from the beginning of the negotiation until an agreement was reached, the results vary from 5 milliseconds up to 250 milliseconds. As expected, in the case when both agents follow boulware strategies, more time tends to be spent until agreement and the contrary is observed when both follow conceder strategies.

The second ecosystem is made up of four members. Fig. 7.14b illustrates the interdependencies within the ecosystem, and Fig. 7.14a the geometry of the original trajectories. AC_1 and AC_2 are the two conflict. AC_3 and AC_4 are the surrounding traffic aircraft. They are both interdependent with AC_1 and with each other. This means that there exist some maneuver that AC_1 can perform by which a conflict between AC_1 and AC_3, or a conflict between AC_1 and AC_4 will be induces. Therefore, the generated regions of AC_1 will be constrained by these two aircraft, contrary to the regions of AC_2.

[4]We consider an agreement near optimal if one of its neighboring points is Pareto optimal.

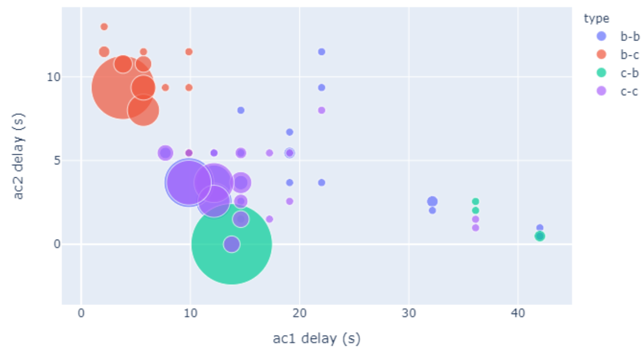
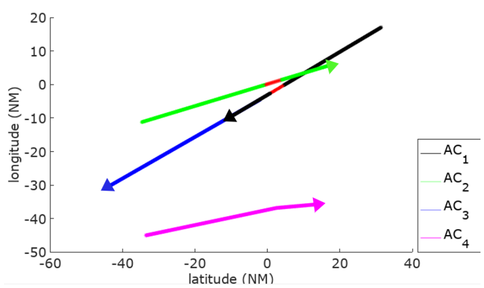
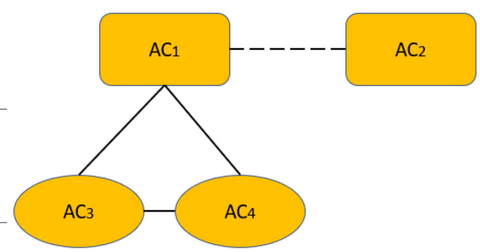


Figure 7.13: Results of the simulated negotiation for the first ecosystem.



(a) The original trajectories of the four aircraft of the second ecosystem in a planar projection.



(b) The interdependencies within the second ecosystem.

Figure 7.14: The geometry and graph of interdependencies for the second ecosystem.

The bottleneck of the regions in the domain was calculated to range from $17.20NM^2$ to $65.24NM^2$.
In Fig. 7.15 and Fig. 7.16 the potential bids are represented for the cases when aircraft consider only delays, or only extra fuel consumption. Again, since both cases have similar shapes, we will depict the simulation results for only one of the them. Fig. 7.17 contains the simulated negotiations outcomes for the case when both aircraft are concerned about delays, and Table 7.5 contains results regarding the efficiency and distribution of costs. When we count near optima solutions, there is a clear distinction between cases when the aircraft use same, or different strategies. This distinction is also evident with respect to how well the costs are distributed.
Depending on how the involved aircraft's strategies differ, there seems to be a clear trade-off between reaching an agreement that lies on the Pareto frontier

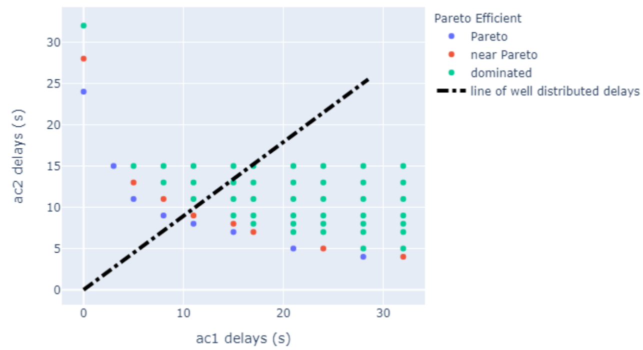


Figure 7.15: The possible bids if both aircraft consider only delays.

ec2	***b-b***	***b-c***	***c-b***	***c-c***
Pareto	45%	36%	74%	34%
near Pareto	60%	100%	98%	59%
well distributed	95%	1%	6%	3%

Table 7.5: Results regarding efficiency of the resolutions and distribution of costs among aircraft for ecosystem 2.

and reaching agreements that distribute the costs between both aircraft.

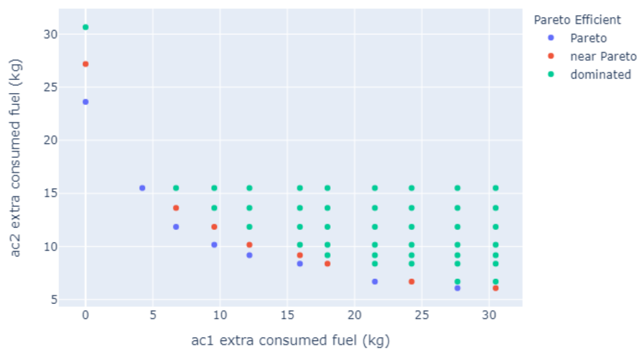


Figure 7.16: The possible bids if both aircraft consider only extra fuel costs.

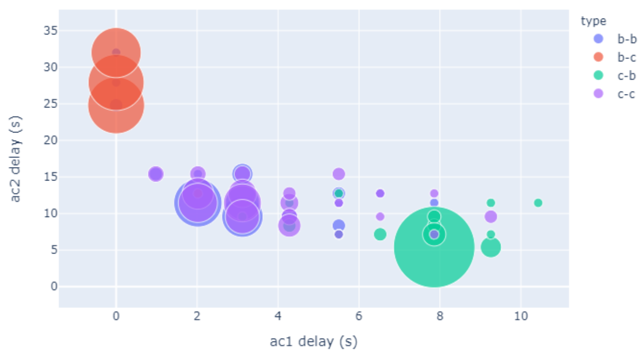


Figure 7.17: Results of the simulated negotiation for the second ecosystem.

Chapter 8

Conclusions & Future Work

8.1 Conclusions

This research aimed to investigate several topics that are not covered in the existing literature of en-route air traffic CD&R. Firstly, to overcome some industrial barriers and improve their acceptability, automatic CR solvers (or advisory systems) should demonstrate resilience in order to be capable to deal with unexpected events. Some level of resilience can be provided through the generation of families of resolutions, instead of unique ones. Nonetheless, most existent works in tactical air traffic CD&R are providing unique resolutions. Secondly, provided resolutions should guarantee that no new conflicts will be induced, at least within a given time window. This implies that complete identification of the relevant surrounding traffic needs to be performed before the computation of a resolution. Despite its importance, existent literature ignores complete surrounding traffic identification. Thirdly, air traffic is a highly dynamic environment, with different actors participating in it. The interests of these actors do not always align. Therefore, in order to improve efficiency, their active participation can be beneficial. Such participation can be made possible, through automatic negotiation. Lastly, air traffic CD&R is a real-time and safety-critical process. In order to successfully implement an automatic negotiation mechanism within its context, the deadline of the delegated negotiation process as well as solutions to be taken in case no agreement is reached need to be known in advance.
The above points are addressed under the following assumptions:

- The ATCo is responsible to take the final decision regarding the CR process. Agents that represent aircraft can only suggest resolution regions. Nevertheless, the functionalities of the agents can be extended to make them capable of taking full responsibility of the CR decision making process in fully automated environments, such as Airbus UTM [33].

- All conflicts are pairwise, i.e. there are no multithreads. However, cases when several pairwise conflicts coexist in time with tight spatial bounds are treated.

- The proposed framework does not consider overtakings, since for them there are already well-accepted procedures.
- False positive conflicts are pre-filtered.
- The used trajectory predictor (TP) is ideal and predicts trajectories in a deterministic manner. However, the framework can be adapted to work with a different TP that is functional in environment that considers uncertainties (such as wind uncertainties).
- No prohibited flying zones are present.
- Each aircraft behaves as a point-mass that follows a piecewise linear trajectory, with piecewise constant velocity in a 3D Euclidean space.
- No communication issues can arise. Moreover, the communication between agents is instantaneous. Nevertheless, the proposed protocols can be adapted to work under more realistic communication scenarios.
- The agents that represent the involved aircraft are always willing and able to initiate a negotiation process.
- The agents representing the aircraft are given decision making autonomy during the automatic negotiation process.

The thesis has made the following contributions:

- Spatio-temporal regions are identified as a mean to achieve some resilience within CR.
- The "bottleneck" method is proposed as a mean to measure the level of resilience for spatio-temporal regions.
- Completeness of the relevant traffic identification is formally defined.
- The aerial ecosystem concept is formalized. Moreover, through the proposed formalization, complete identification can be performed and no relevant members are missed.
- The spatio-temporal interdependencies, based on which the ecosystem concept is defined, have been implemented in a computationally efficient (and therefore also feasible) way.
- A quantitative analysis of the ecosystems formed in nowadays traffic, as well and in some projected traffic scenarios, has been performed.
- Interdependencies between ecosystems have been defined.

- A quantitative analysis on the effectiveness of several strategies to mitigate the bounds between ecosystems has been performed.

- We have adopted an automated negotiation mechanism through which airlines can actively participate in the CR process. The proposed mechanism is decentralized, considers relevant surrounding traffic, and offers some level of resilience. Moreover, existent literature, relevant to the application of automatic negotiation in the context of CR, imposes constraints on the way involved parties can offer bids to each other[1]. Differently from that, the mechanism proposed in this thesis allows the involved parties to choose their negotiating tactics and decide what bid to offer at each time instance on their own.

- An initial approach, by which the latest possible resolution can be identified, has been proposed. The corresponding time can be used as a deadline for the negotiation process.

8.2 Future Work

Potential extensions of this work can be of various natures. Using a rough classification, we can distinguish future works relevant to further technical improvements, to the relaxation of some of the working hypotheses, to the adaptation of the proposed techniques for use in the USPACE context, or to the use of the methodologies in a different context.

1. ***Consideration of intent uncertainties***
   In this work we assume that all aircraft know the intent of each other. This can be true in the context of TBO, or the current structured traffic. However, under the concept of free routing this assumption relaxes. There, aircraft know the desired point of arrival of one another, but do not have any information regarding the route each intents to follow. Therefore, to make use of spatio-temporal regions in CR for those cases, some adaptations need to be performed.

2. ***Consideration of wind uncertainties***
   In realistic traffic, wind can affect the trajectory, or velocity of the aircraft. Therefore, the assumption of no present wind has to be discarded. In order to consider the location uncertainties, we can argue that a change of the initial state of the region[2] can be enough. On the other hand, to consider velocity uncertainties, the current regions will be extended. As an example, in the case of the regions based on heading, this extension can be made possible using the ideas present in the regions based on velocity alteration. In this way the constructed regions will include trajectories based on heading and velocity module change.

[1] The cost of the offered bids must monotonically increase, as time passes by.
[2] Instead of an initial point, an initial polygon needs to be considered.

3. ***Consideration of restricted zones***
   Restricted zones are occasionally present in the airspace. The restriction can be a result of military activities being performed in the area, bad weather conditions, etc. Cases when the constructed spatio-temporal regions are affected by restricted zones can be considered.

4. ***Consideration of more realistic aircraft dynamics***
   In this work, the aircraft is modeled as point mass that travels in a piece-wise linear trajectories, with piece-wise constant velocities. In order to move towards industrial applications, more realistic aircraft dynamics need to be considered. Such considerations will not drastically change the mathematical description of the regions, they can affect though the effectiveness of the proposed cuts, which will need to be adapted accordingly.

5. ***Use of hextree subdivisions to speed up ecosystem identification***
   As mentioned in Chapter 4, the use of hextree subdivisions method could improve the computational efficiency of the identification process.

6. ***Unification of the resilience measure.***
   The proposed "bottleneck" method provides a measure of resilience that is adapted to the spatial dimensionality of the spatio-temporal regions. This imply that, at its current form, a comparison between the level of resilience of spatio-temporal region based on heading alteration and a region that avoids delays generation cannot be performed. Moreover, the method does not generalizes for CR solvers that can provide a finite set of resolutions. In order to make comparison possible, a unified resilience measure is necessary.

7. ***Consideration of the airline performance and pilot skills in the initialization and modification of the regions' borders***
   The methodology we use to construct the spatio-temporal regions, considers geometric limitations and the desired intent of the aircraft. A way to customize and further refine these regions is by considering more factors in their constructions. Two examples of such factors are the performance of the airline and the pilot's skills. By considering the airline's performance, which within our settings is done by considering the cost function of the aircraft, we can construct regions that contain safe trajectories that are more efficient. Consideration of the pilots' skills could also minimize the costs. A skilled pilot can be more precise in her/his maneuvers and therefore can operate with regions that are less resilient, i.e. have a smaller bottleneck.

8. ***Use of more information during the estimation of the cost of a region***
   We assign to each region the cost of the trajectory that lies within the region and minimizes deviation from the original trajectory. This approach can be refined to account for the fact that as time passes, the set of all potential resolutions shrinks. Moreover, consideration of the cost index

can further improve the changes of an agent to obtain a good agreement for itself. An aircraft that seeks to preserve fuel consumption, is interested in resolution trajectories that minimize its fuel costs. On the other hand an aircraft that seeks to not introduce much delay in its route, is interested in resolution trajectories that minimize delays.

9. ***Provision of adequate human-machine interfaces (HMIs)*** The outcome of the negotiation process is a set of pairs of safe spatio-temporal conflict-free regions. Within these regions, resolution trajectories will be chosen. In case the final trajectories are going to be constructed by a human (e.g. an ATCo, or a pilot), then some Human Machine Interface (HMI) to represent the regions is necessary. Klomp et al. [111] provide some visualization in cases when a single aircraft maneuvers and all the rest maintain their original trajectories. This approach needs to be generalized to account for cases when several aircraft have to maneuver.

10. ***Optimization of the trajectory generation within a conflict-free region***
If the final trajectories are going to be constructed in an automatic manner (e.g. each aircraft's FMS is required to do so), a supportive algorithm can be provided. This algorithm will perform the trajectory construction in an efficient manner, according to the cost preferences of the aircraft.

11. ***Estimation of potential future influence that a resolution might have***
In the case of heading-based regions, which induce delays in the system, and under high-density scenarios, it is necessary to consider future effects, beyond the existence time interval of an ecosystem. This would allow the negotiating parties to achieve solutions which will cause minimal (if any) disruptions in the management of flows & capacity. Future effects can be considered by estimating the influence that potential resolutions can have to the complexity of the traffic[3]. Such estimations can be based on Machine Learning techniques [113].

12. ***Extend the deadlock estimation algorithms***
The algorithms proposed to identify the latest resolution for a given ecosystem, identify resolutions that include a single aircraft maneuvering. However, under bad weather conditions, or in dense traffic scenarios cases when more than a single aircraft will need to maneuver can be present. Moreover, in certain scenarios maneuvering more than one aircraft could generate a later deadlock. Therefore, possible extensions of the algorithms to account for such scenarios need to be investigated.

13. ***Adaptation of negotiation protocols, where more than two members can actively negotiate***

[3]For a summary of complexity metrics and a qualitative comparison among them, the reader can refer to [112]

The negotiation protocol we currently use supports negotiation between two parties. As reported, in Chapter 2, various extensions have already been proposed in literature. Yet, they assume that involvement of all parties in the negotiation is equally important. In the context of CR, the participation of ecosystem members of different orders is not equally important (e.g. the participation of a second order ecosystem member is not as important as the participation of an aircraft involved in a conflict). Use of this information by the negotiation protocol can facilitate the occurrence of the negotiation process, even in cases when some of the ecosystem members cannot participate in it (e.g. because they have communication issues).
Furthermore, in his seminal work [114], Gruber defines an ontology to be an explicit specification of a conceptualization. The definition of conceptualization is taken from Genesereth and Nilsson [115] and reads, "A body of formally represented knowledge is based on a conceptualization: the objects,concepts, and other entities that are assumed to exist in some area of interest and therelationships that hold among them". The exact formal relationships and information that the agents will exchange under these protocols should be formalized.

14. ***Consider qualitative preferences of ATCos & the pilots***
As mentioned in Chapter 7, ATCo tend to prefer resolutions based on heading change, rather than resolutions based on speed change. Furthermore, the pilots prefer heading-based resolutions to altitude-based resolutions. If agents are allowed to negotiation, regions based different maneuvers (i.e. heading-based, speed-based, altitude-based, or compound ones), these qualitative preferences need to be considered. The technical mechanisms of doing such thing possible vary from differentiating cost functions of regions according to the maneuvers they are based on, to letting parties negotiate sequentially. In case a sequential negotiation is chosen, the parties can be intent firstly to achieve resolutions based on heading regions and in case an agreement is not reached, let them negotiate with the rest of the regions types.

15. ***Use of spatio-temporal interdependencies in other solvers***
The identification of spatio-temporal interdependencies can help in the reduction of computational costs for solvers proposed in literature, by providing two benefits. Firstly, it can reduce the total number of aircraft that needs to considered by the solver. This since through the simplistic, classical spatial identification method that other CD&R solvers use, a lot of redundant aircraft are considered in the solution process. Secondly, it can reduce the number of constrains the solver needs to consider. As an example, in the way the CR is currently modeled through MINP, there is a constraint for each pair of aircraft, to guarantee that no separation infringement occurs. However, after we identify the pairwise interdependencies, the constraints for pair of aircraft that are not interdependent can be safely omitted in the MINP model.

16. ***Use of extended spatio-temporal interdependencies to provide better situational awareness (SA) to the ATCo, when an aircraft asks for a direct***
Under nowadays structured traffic, the aircraft does not always follow the pre-defined sequence of waypoints of its route. At times, pilots ask the ATCo for a permission to skip some of the waypoints[4]. The ATCo, based on the situation of the traffic he has to manage and on how such a diversion would affect it, decides to authorize the maneuver, or not. This procedure adds extra workload for the ATCo. One way to provide support under these circumstances, is through a tool that could identify the spatio-temporal interdependencies within the sector. Such a tool can provide the information regarding the interdependencies present in the sector to ATCo and help in the decision making.

17. ***Use of extended spatio-temporal interdependencies to provide better SA to the pilot, before she/he asks for a direct***
One way to tackle situations when a direct is asked is to assist the ATCo in the decision making. Another one is by assisting the pilot so he/she can make informed requests. A similar system to the one proposed to serve the ATCo can be present on the aircraft side. Given such a system, requests which could cause disruptions to the sector can be pre-filtered and not sent to the ATCo.

18. ***Use of extended spatio-temporal interdependencies to in order to recommend to the pilot safe, feasible direct requests***
Going a step further, a system could even identify feasible directs that are safe to apply, before the pilot. After such directs are identified, they can be presented to the pilot. In case he/she approves them, the request can be communicated to the ATCo.

19. ***Use of spatio-temporal interdependencies to provide better SA in the context of flight centric ATC***
An approach proposed in literature to tackle the capacity problem is flight centric ATC [116]. The idea behind it is to dissolve sector boundaries and assign to an ATCo aircraft throughout their flight. Such an assignment does not need to be based on geographic criteria. The approach raises several issues. As reported by Martins et al. [117], ATCos identify the lack of SA as a mayor problem. Spatio-temporal interdependencies can be used to identify the dependencies between nearby aircraft and improved the SA.

20. ***The use of negotiated CR in the context of flight centric ATC***
Another issue that arises with flight centric ATC is related to CR. In scenarios when aircraft controlled by different ATCos are in conflict, it is unclear who would be responsible to resolve the conflict and how. In

[4] In a scenario where an aircraft has accumulated some delay, it might seek such a deviation in order to recuperate.

order to treat all involved ATCos equally, an automatic negotiation could be used to resolve the conflict. In that case, the negotiating parties will represent the ATCos, and not the airlines.

21. ***Applications within systems of Autonomous Guided Vehicles***
In an environment where several Autonomous Guided Vehicles (AGVs) are operating, potential conflicts can arise. The use of spatio-temporal interdependencies can improve the SA of the included vehicles. Furthermore, a CR can be negotiated.

22. ***Adaptation for tactical conflict resolution in the context of U-space***
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 Unmanned Aircraft Systems (UASs) [74]. Within its context, Concept of Operations for U-Space (CORUS) was an exploratory research project, aiming to define concept of operations, that will allow manned and unmanned aircraft to coexist safely [118]. Among its proposals, is the introduction of three airspace classes for the airspace where UAS operate. Class Z would cover high-density environment as airspace over airports and urban environment. The class is further divided into Class Za, which covers airspace over airports, and Class Zu, including the airspace over urban environment. Within both classes tactical CR needs to be offered [119]. In Class Za tactical CR will be offered by the ATCo, while in Class Zu tactical CR will be offered through U-space.
The introduction of of air vehicles (manned and unmanned) that deliver goods, or transport people, within urban environments is known as Urban Air Mobility (UAM). The concept is being explored by various entities, including SESARJU, through the U-space concept [74], NASA [120], Airbus [121], and Uber [122].
Among the proposed ideas, it is argued that because of the expected high density and versatility of the air vehicles, ATM in its current form would be unable to deal with the traffic. An Unmanned Traffic Management (UTM) system deployment is proposed as an alternative [123]. Within such a system, fully automatic CR is mandatory.

23. ***Studies regarding the locus of the CR system***
The locus of the automated negotiation CR has to be determined. Such system is decentralized, but is not necessarily distributed. A possible non-distributed version could have agent entities that represent negotiating aircraft in the ATC Center (ATCC). On the other hand a distributed version can have various shape. The software agent representing each aircraft can be on board. An alternative to this would be for each airline to have its agents at its Flight Control Center.
In order to take this decisions, a discussion of the desired level of CR delegation is necessary. Furthermore, various architectures of the system will raise different communication challenges that will need to be addressed.

A similar analysis needs to be performed within the context of USPACE as well in order to be able to apply our methodologies there.

Appendices

Appendix A

Regions based on velocity module, or altitude change

In this chapter we will provide the mathematical formulation for spatio-temporal regions based solely on altitude, or horizontal velocity module change. The ideas used are similar to the ones adopted to constructed the regions based on heading change.

A.1 Spatio-temporal Regions Implementation Based on Altitude Change

Spatio-temporal regions that consider altitude changes are simpler than regions baased on heading change since the parameter space is one dimensional. A two dimensional set bounded by segments and an arc, translates to a segment in a one dimensional space. Therefore, the altitude-based regions are evolving segments, which analogously to the heading alteration case, can be divided into two cases (shown in Fig. A.1 and Fig. A.2). The case where the region (in this case linear segment) initially where the aircraft ascends to avoid the conflict and then descends to go back to the original trajectory and another one descending to avoid the conflict and then ascending to reach the original trajectory. The ascending parts are bounded by the original trajectory and the points that can be achieved at each time instance using the maximum ascending rate and the descending parts are bounded by the original trajectory and the points that can be achieved at each time instance using the maximum descending rate.

Loss of vertical separation of altitude-based regions

The evolution of the distance between two moving segments is described by:

$$d([z_{1,1}(t)z_{1,2}(t)],[z_{2,1}(t)z_{2,2}(t)]) := \min_{i,j\in 1,2} d([z_{i,1}(t)z_{i,2}(t)], z_{3-i,j}(t))$$

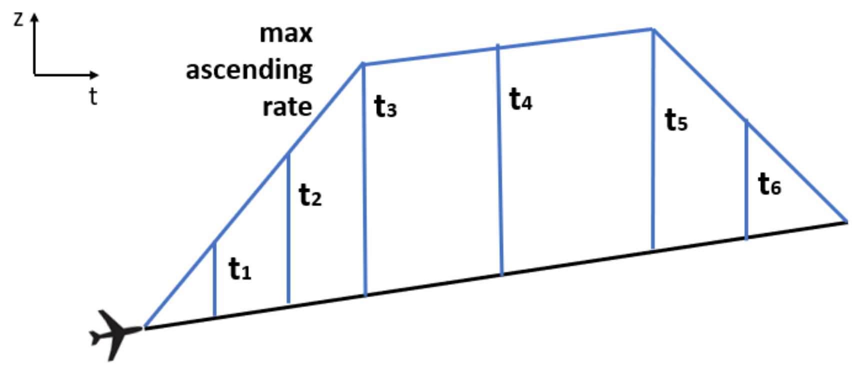


Figure A.1: Example of an upper altitude region

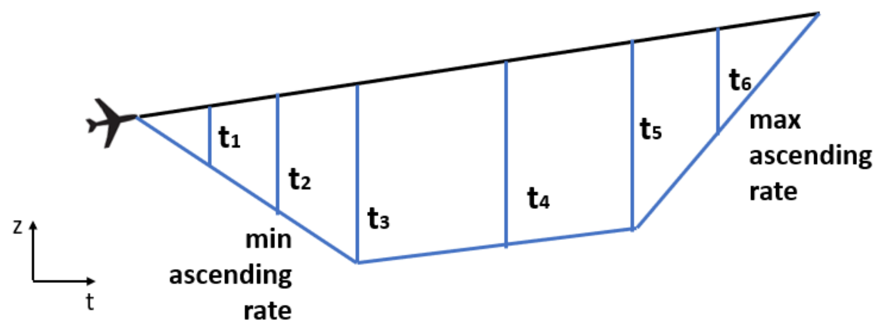


Figure A.2: Example of a lower altitude region

where $z_{i,j}(t) = v_z t + z_{0,i,j}$ describes the altitude dynamics of the aircraft during the linear segment.
A loss of vertical separation between an evolving point, $z_{1,1}(t)$, and an evolving segment, $[z_{2,1}(t), z_{2,2}(t)]$ occurs if and only if:

$$[||z_{1,1}z_{2,1}(t)|| < V] \vee [||z_{1,1}(t)z_{2,2}(t)|| < V] \vee [||z_{2,1}(t) \leq z_{1,1}(t) \leq z_{2,2}(t)] \quad \text{(A.1)}$$

where V is the standard vertical separation constant.
Similar to the heading case, some straightforward mathematical manipulations can transform, also, these inequations to a second order polynomial inequality, which can be solved analytically.

A.2 Spatio-temporal Regions Implementation Based on Horizontal Velocity Module Change

Applications can be found in constructing regions based on changes in the horizontal velocity module, too. The simplest regions would be the ones where velocity is initially decreased to avoid the conflict and then increased to minimize the introduced delay and another where the aircraft increases its velocity to avoid the region and then decreases it again.

A.2.1 Loss of separation between velocity-module-based regions

The evolution of the distance between two moving segmens is described by an equation with the same form to Eq. 3.11, however here, instead of being able to change the whole velocity vector, we can only adapt its module. This can be reflected in the equation of motion through the addition of a constant. More specifically, let $\vec{p_1}(t)$ be one of the end points of the moving segment, then:

$$\vec{p_1}(t) = (1+\alpha)\vec{v_1}t + \vec{p_{01}} \tag{A.2}$$

where $\vec{v_1}$ is the horizontal velocity of the aircraft, $\vec{p_{01}}$ its location at the beginning of the interval and α a constant with values $\alpha \in [-0.06, 0]$ in the parts where we have decreasing velocity and $\alpha \in [0, 0.03]$ in the parts where we have increasing velocity. The values for the maximal increment and decrement of the velocity module are choosen after consultation with previous relevant works [42, 71].
Given the above clarification, the procedure follows the same path to achieve polynomial inequalities of second order which we can solve analytically.

Appendix B

List of Acronyms

- **AD** → Aircraft Density
- **AGV** → Autonomous Guided Vehicle
- **AIS** → Aeronautical Information Services
- **AMAN** → Arrival Manager
- **ANAC** → Automated Negotiating Agents Competition
- **ANS** → Air Navigation services
- **AS** → Alerting Service
- **ASM** → Airspace Management
- **ATC** → Air Traffic Control service
- **ATCC** → ATC Center
- **ATCo** → Air Traffic Controller
- **ATFCM** → Air Traffic Flow and Capacity Management
- **ATFM** → Air Traffic Flow Management
- **ATM** → Air Traffic Management
- **ATS** → Air Traffic Services
- **CD&R** → Conflict Detection & Resolution
- **CNS** → Communication, Navigation, and Surveillance services
- **CP** → Constraint Programming
- **CPA** → Closest Point of Approach

- **CR** → Conflict Resolution
- **CTA** → Controlled Areas
- **DD** → Dynamic Density
- **DDR II** → Demand Data Repository II
- **FAB** → Functional Airspace Blocks
- **FD** → Fractal Dimension
- **FDP** → Flight Data Processor
- **FIR** → Flight Information Region
- **FIS** → Flight Information Service
- **FL** → Flight Level
- **Flight Management System** → Flight Management System
- **ft** → feet
- **GENIUS** → General Environment for Negotiation with Intelligent multipurpose Usage Simulation
- **HMI** → Human-Machine Interface
- **IC** → Interval Complexity
- **IFR** → Instrumental Flight Rules
- **InComp** → Intrinsic Complexity
- **KPI** → Key Performance Indicator
- **MAS** → Multi-Agent System
- **MET** → METeorological services for air navigation services
- **MINP** → Mixed-Integer Nonlinear Programming
- **NM** → Nautical Miles
- **SA** → Situational Awareness
- **SAR** → Search And Rescue services
- **SORA** → Specific Operations Risk Assessment
- **STCA** → Short Term Conflict Alert
- **TBO** → Trajectory-Based Operations

- **T-CAS** → Traffic alert and Collision Avoidance System
- **TLS** → Target Level of Safety
- **TP** → Trajectory Predictor
- **UAM** → Urban Air Mobility
- **UAS** → Unmanned Aerial System
- **UIR** → Upper Information Region
- **UTM** → Unmanned Traffic Management
- **VFR** → Visual Flight Rules

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Bibliography

[1] Jay Macpherson and Robert Graves. The Greek Myths. *Phoenix*, 12(1):15, 1958.

[2] Firdawsi, Arthur George Warner, and Edmond Warner. *The Sháhnáma of Firdausí*. K. Paul, Trench, Trübner & Company Limited, 1906.

[3] Andrew Cook. *European Air Traffic Management*. Routledge, dec 2016.

[4] ICAO. Annual Report of the Council - 2018. Technical report, ICAO, 2018.

[5] European Comission. COMMISSION IMPLEMENTING REGULATION (EU) 2017/373 of 1 March 2017 laying down common requirements for providers of air traffic management/air navigation services and other air traffic management network functions and their oversight, repealing Regulation (EC) No 482/2008, Implementing Regulations (EU) No 1034/2011, (EU) No 1035/2011 and (EU) 2016/1377 and amending Regulation (EU) No 677/2011. Technical report, European Comission, 2017.

[6] Jeff Edwards. The Most Deadly Aviation Accidents in History, oct 2019.

[7] ICAO. Manual on Global Performance of the Air Navigation System. Technical report, ICAO, 2009.

[8] ICAO. Annex 6 - Operation Of Aircraft - Part I - International Commercial Air Transport - Aeroplanes. Technical report, ICAO, 2018.

[9] ICAO. Universal Safety Oversight Audit Programme - Continuous Monitoring Manual (doc. 9735). Technical report, ICAO, 2011.

[10] EUROCONTROL Performance Review Commission. Performance Review Report, An Assessment of Air Traffic Management in Europe during the Calendar Year 2018. Technical report, EUROCONTROL, 2019.

[11] Javier López-Leonés, Manuel Polaina Morales, Pablo Sánchez Escalonilla, Damián Ferrer Herrer, Marcos Sanz Bravo, Fernando Celorrio Cámara, and Ángel Martínez Mateo. User-centric Cost-based Flight Efficiency and Equity Indicators. In *SIDS*, 2017.

[12] Y. Shoham Leyton-Brown, K., Yoav Shoham, and Kevin Leyton-brown. *Multiagent Systems: Algorithmic, Game-theoretic, and Logical Foundations by Y. Shoham and K. Leyton-Brown Cambridge University Press, 2008*. 2010.

[13] John Nash. Non-Cooperative Games. *The Annals of Mathematics*, 1951.

[14] B. Lockwood. Pareto efficiency. In *The New Palgrave Dictionary of Economics*, page 1. Nature Publishing Group, feb 2011.

[15] Roger B. Myerson. Utilitarianism, Egalitarianism, and the Timing Effect in Social Choice Problems. *Econometrica*, 1981.

[16] ICAO. PANS-ATM Procedures for Air Navigation Services - Air Traffic Management (Doc 4444) 16th edition. Technical report, ICAO, 2016.

[17] ICAO. Oversight Manual - The Establishment and Management of a State's Aviation Security Oversight System, part B (Doc 9734). Technical report, ICAO, 2006.

[18] EUROCONTROL. ATFCM Operations Manual. Technical report, EUROCONTROL, 2019.

[19] ICAO. Rules of the Air. Technical report, ICAO, 2005.

[20] ICAO. Annex 11 - Air Traffic Services, 15th Edition. Technical report, ICAO, 2018.

[21] Francisco Javier Sáez Nieto. The long journey toward a higher level of automation in ATM as safety critical, sociotechnical and multi-Agent system. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 2015.

[22] ICAO. Manual on Air Traffic Management System Requirements (doc. 9882). Technical report, ICAO, 2008.

[23] Giulio Di Gravio, Maurizio Mancini, Riccardo Patriarca, and Francesco Costantino. Overall safety performance of the air traffic management system: Indicators and analysis. *Journal of Air Transport Management*, 2015.

[24] Andrew Cook, Seddik Belkoura, and Massimiliano Zanin. ATM performance measurement in Europe, the US and China. *Chinese Journal of Aeronautics*, 2017.

[25] SESAR. Trajectory-Based Operations.

[26] SESAR. European ATM Master Plan. Technical report, SESAR, 2020.

[27] EUROCONTROL. Safety Nets, A guide for ensuring effectiveness. Technical report, EUROCONTROL, 2017.

[28] James K Kuchar and Lee C Yang. A Review of Conflict Detection and Resolution Modeling Methods. *IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS*, 1(4), 2000.

[29] Rogier Woltjer, Ella Pinska-Chauvin, Tom Laursen, and Billy Josefsson. Resilience engineering in air traffic management: Increasing resilience through safety assessment in SESAR. In *SIDs 2013 - Proceedings of the SESAR Innovation Days*, 2013.

[30] Romaric Breil, Daniel Delahaye, Laurent Lapasset, and Eric Féron. Multiagent Systems to Help Managing Air Traffic Structure. *Special Issue on Strategic TFM. <hal*, page 1567694, 2017.

[31] Amy R Pritchett and Antoine Genton. Negotiated Decentralized Aircraft Conflict Resolution. *IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS*, 1, 2017.

[32] Marko Radanovic, Miquel Angel Piera Eroles, Thimjo Koca, and Juan Jose Ramos Gonzalez. Surrounding traffic complexity analysis for efficient and stable conflict resolution. *Transportation Research Part C: Emerging Technologies*, 2018.

[33] Airbus. Airbus UTM.

[34] Jun Tang, Miquel Angel Piera, and Toni Guasch. Coloured Petri net-based traffic collision avoidance system encounter model for the analysis of potential induced collisions. *Transportation Research Part C: Emerging Technologies*, 67:357–377, 2016.

[35] Jianghai Hu, Maria Prandini, and Shankar Sastry. Optimal Coordinated Maneuvers for Three-Dimensional Aircraft Conflict Resolution. *Journal of Guidance, Control, and Dynamics*, 2002.

[36] L Pallottino, E M Feron, and A Bicchi. Conflict Resolution Problems for Air Traffic Management Systems Solved With Mixed Integer Programming. *IEEE Transactions on Intelligent Transportation Systems*, 2002.

[37] Arthur Richards and Jonathan P. How. Aircraft trajectory planning with collision avoidance using mixed integer linear programming. In *Proceedings of the American Control Conference*, 2002.

[38] Manolis Christodoulou and Constantinos Costoulakis. Nonlinear Mixed Integer Programming for Aircraft Collision Avoidance in Free Flight. In *IEEE Melecon*, 2004.

[39] Adan E. Vela, Senay Solak, John Paul B. Clarke, William E. Singhose, Earl R. Barnes, and Ellis L. Johnson. Near real-time fuel-optimal en route conflict resolution. *IEEE Transactions on Intelligent Transportation Systems*, 2010.

[40] Henri Augris, Adan E.vela, Erwan Salaun, Maxime Gariel, and Eric Feron. A conflict resolution algorithm for reduced controller taskload. In *AIAA Infotech at Aerospace 2010*, 2010.

[41] Antonio Alonso-Ayuso, Laureano F. Escudero, and F. Javier Martín-Campo. A mixed 0-1 nonlinear optimization model and algorithmic approach for the collision avoidance in ATM: Velocity changes through a time horizon. *Computers and Operations Research*, 2012.

[42] Sonia Cafieri and Nicolas Durand. Aircraft deconfliction with speed regulation: New models from mixed-integer optimization. *Journal of Global Optimization*, 2014.

[43] Lin Quan Fang, Kai Quan Cai, Yang Yang, and Yan Bo Zhu. Decentralized Multi-aircraft Conflict Resolution in the presence of uncertainty. In *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*, 2015.

[44] Antonio Alonso-Ayuso, Laureano F. Escudero, F. Javier Martín-Campo, and Nenad Mladenović. A VNS metaheuristic for solving the aircraft conflict detection and resolution problem by performing turn changes. *Journal of Global Optimization*, 2015.

[45] A. Alonso-Ayuso, L.F. Escudero, and F.J. Martín-Campo. Exact and approximate solving of the aircraft collision resolution problem via turn changes. *Transportation Science*, 2016.

[46] Antonio Alonso-Ayuso, Laureano F. Escudero, and F. Javier Martín-Campo. An exact multi-objective mixed integer nonlinear optimization approach for aircraft conflict resolution. *TOP*, 2016.

[47] Manuel Soler, Maryam Kamgarpour, Javier Lloret, and John Lygeros. A Hybrid Optimal Control Approach to Fuel-Efficient Aircraft Conflict Avoidance. *IEEE Transactions on Intelligent Transportation Systems*, 2016.

[48] Sonia Cafieri and Riadh Omheni. Mixed-integer nonlinear programming for aircraft conflict avoidance by sequentially applying velocity and heading angle changes. *European Journal of Operational Research*, 2017.

[49] Sonia Cafieri, Loïc Cellier, Frédéric Messine, and Riadh Omheni. Combination of optimal control approaches for aircraft conflict avoidance via velocity regulation. *Optimal Control Applications and Methods*, 2018.

[50] Yang Yang, Kai-Quan Cai, and Maria Prandini. Fast Algorithm Based on Computational Geometry for Probabilistic Aircraft Conflict Detection. 2017.

[51] Yang Yang, Jun Zhang, Kai-Quan Cai, and Maria Prandini. A stochastic reachability analysis approach to aircraft conflict detection and resolution. 2014.

[52] Yang Yang, Jun Zhang, Kai-Quan Cai, and Maria Prandini. Multi-aircraft Conflict Detection and Resolution Based on Probabilistic Reach Sets. *IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY*, 25(1), 2017.

[53] Andrea Lecchini Visintini, William Glover, John Lygeros, Jan Maciejowski, W Glover, and J Maciejowski. Monte Carlo Optimization for Conflict Resolution in Air Traffic Control. *IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS*, 7(4), 2006.

[54] Clément Peyronne, Andrew R. Conn, Marcel Mongeau, and Daniel Delahaye. Solving air traffic conflict problems via local continuous optimization. *European Journal of Operational Research*, 2015.

[55] Emre Koyuncu, Mevlut Uzun, and Gokhan Inalhan. Cross-entropy-based cost-efficient 4D trajectory generation for airborne conflict resolution. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 2016.

[56] Agnaldo Volpe Lovato, Cristiano Hora Fontes, Marcelo Embiruçu, and Ricardo Kalid. A fuzzy modeling approach to optimize control and decision making in conflict management in air traffic control. *Computers & Industrial Engineering*, 2018.

[57] Christian Bongiorno, Salvatore Miccichè, and Rosario N. Mantegna. An empirically grounded agent based model for modeling directs, conflict detection and resolution operations in air traffic management. *PLoS ONE*, 2017.

[58] EUROCONTROL, CENA, STNA, NLR, RLD, LVNL, DLR, DFS, UK CAA, NATS, and DERA. PHARE. https://www.eurocontrol.int/phare/public/standard_page/Overview.html. Accessed: 2020-03-30.

[59] ONERA, Alenia Aeronautica, CIRA, DLR, ENAC, Erdyn Consultans, Israel Aerospace Industries, Monitor Soft, NLR, Technion Israel Institute of Technology, Thales Communications France, TsAGI, and University of Patras. 4DCo-GC. http://www.4dcogc-project.org/. Accessed: 2020-03-30.

[60] Siqi Hao, Yaping Zhang, Shaowu Cheng, Ruiwei Liu, and Zhiwei Xing. Probabilistic multi-aircraft conflict detection approach for trajectory-based operation. *Transportation Research Part C: Emerging Technologies*, 2018.

[61] Siqi HAO, Shaowu CHENG, and Yaping ZHANG. A multi-aircraft conflict detection and resolution method for 4-dimensional trajectory-based operation. *Chinese Journal of Aeronautics*, 31(7):1579–1593, jul 2018.

[62] Marco Dorigo and Christian Blum. Ant colony optimization theory: A survey. *Theoretical Computer Science*, 344(2-3):243–278, nov 2005.

[63] Martin S Eby. A Self-Organizational Approach for resolving Air Traffic Conflicts. *The Lincoln Laboratory Journal*, 1994.

[64] Giannis Roussos and Kostas J. Kyriakopoulos. Completely decentralised Navigation Functions for agents with finite sensing regions with application in aircraft conflict resolution. In *Proceedings of the IEEE Conference on Decision and Control*, 2011.

[65] Laureline Guys, Stéphane Puechmorel, and Laurent Lapasset. Automatic Conflict Solving using Biharmonic Navigation Functions. *Procedia - Social and Behavioral Sciences*, 2012.

[66] Jerom Maas, Emmanuel Sunil, Joost Ellerbroek, and Jacco Hoekstra. The Effect of Swarming on a Voltage Potential-Based Conflict Resolution Algorithm. 2016.

[67] Jared C. Hill, F. Ryan Johnson, James K. Archibald, Richard L. Frost, and Wynn C. Stirling. A cooperative multi-agent approach to free flight. 2005.

[68] J C Hill, J K Archibald, W C Stirling, and R L Frost. A multi-agent system architecture for distributed air traffic control. *Network*, 2005.

[69] James K. Archibald, Jared C. Hill, Nicholas A. Jepsen, Wynn C. Stirling, and Richard L. Frost. A satisficing approach to aircraft conflict resolution. *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews*, 2008.

[70] Wynn C Stirling. Social Utility Functions—Part I: Theory. *IEEE Transactions on Systems, Man and Cybernetics, Part C: Applications and Reviews*, 35(4), 2005.

[71] Romaric Breil, Daniel Delahaye, Laurent Lapasset, and Eric Féron. Multi-agent Systems for Air Traffic Conflicts Resolution by Local Speed Regulation. *7th International Conference on Re- search in Air Transportation (ICRAT 2016)*, 2016.

[72] Karl D. Bilimoria. Survey of air/ground and human/automation functional allocation for separation assurance. In *12th AIAA Aviation Technology, Integration and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2012.

[73] Yazdi I. Jenie, Erik Jan Van Kampen, Joost Ellerbroek, and Jacco M. Hoekstra. Taxonomy of Conflict Detection and Resolution Approaches for Unmanned Aerial Vehicle in an Integrated Airspace. *IEEE Transactions on Intelligent Transportation Systems*, 2017.

[74] SESARJU. U-space Blueprint. Technical report, Sesar Joint Undertaking, Blussels, 2017. Accessed: 2020-05-03.

[75] JARUS. JARUS guidelines on Specific Operations Risk Assessment (SORA). Technical report, 2017.

[76] Edward J. Lawler and Dean G. Pruitt. Negotiation Behavior. *Industrial and Labor Relations Review*, 36(2):301, jan 1983.

[77] James J. Opaluch and Kathleen Segerson. Rational Roots of "Irrational" Behavior: New Theories of Economic Decision-Making. *Northeastern Journal of Agricultural and Resource Economics*, 18(2), 1989.

[78] Konstantinos Tsetsos, Rani Moran, James Moreland, Nick Chater, Marius Usher, and Christopher Summerfield. Economic irrationality is optimal during noisy decision making. *Proceedings of the National Academy of Sciences of the United States of America*, 113(11), 2016.

[79] Christian Julmi. When rational decision-making becomes irrational: a critical assessment and re-conceptualization of intuition effectiveness. *Business Research*, 12(1), 2019.

[80] Mukun Cao, Xudong Luo, Xin Luo, and Xiaopei Dai. Automated negotiation for e-commerce decision making: A goal deliberated agent architecture for multi-strategy selection. *Decision Support Systems*, 2015.

[81] Hamid Jazayeriy, Masrah Azmi-Murad, Nasir Sulaiman, and Nur Izura Udizir. The learning of an opponent's approximate preferences in bilateral automated negotiation. *Journal of Theoretical and Applied Electronic Commerce Research*, 2011.

[82] Bahador Shojaiemehr, Amir Masoud Rahmani, and Nooruldeen Nasih Qader. Cloud computing service negotiation: A systematic review. *Computer Standards and Interfaces*, 2018.

[83] Bo An. *Automated negotiation for complex multi-agent resource allocation.* PhD thesis, 2010.

[84] Ariel Rubinstein. Perfect Equilibrium in a Bargaining Model. *Econometrica*, 1982.

[85] Shaheen Fatima, Sarit Kraus, and Michael Wooldridge. *Principles of automated negotiation.* 2014.

[86] Chaim Fershtman and Daniel J. Seidmann. Deadline effects and inefficient delay in bargaining with endogenous commitment. *Journal of Economic Theory*, 1993.

[87] Reyhan Aydoğan, David Festen, Koen V. Hindriks, and Catholijn M. Jonker. Alternating offers protocols for multilateral negotiation. *Studies in Computational Intelligence*, 2017.

[88] Mark Klein, Peyman Faratin, Hiroki Sayama, and Yaneer Bar-Yam. Protocols for Negotiating Complex Contracts, 2003.

[89] T. N. Wong and Fang Fang. A multi-agent protocol for multilateral negotiations in supply chain management. *International Journal of Production Research*, 2010.

[90] Colin R. Williams, Valentin Robu, Enrico H. Gerding, and Nicholas R. Jennings. Negotiating concurrently with unknown opponents in complex, real-time domains. In *Frontiers in Artificial Intelligence and Applications*, 2012.

[91] Reyhan Aydoğan, Koen V. Hindriks, and Catholijn M. Jonker. Multilateral mediated negotiation protocols with feedback. In *Studies in Computational Intelligence*. 2014.

[92] Dave de Jonge and Carles Sierra. NB3: a multilateral negotiation algorithm for large, non-linear agreement spaces with limited time. *Autonomous Agents and Multi-Agent Systems*, 2015.

[93] Peyman Faratin, Carles Sierra, and Nick R. Jennings. Negotiation decision functions for autonomous agents. *Robotics and Autonomous Systems*, 1998.

[94] Catholijn M. Jonker, Reyhan Aydoğan, Tim Baarslag, Katsuhide Fujita, Takayuki Ito, and Koen Hindiks. Automated negotiating agents competition (ANAC). In *31st AAAI Conference on Artificial Intelligence, AAAI 2017*, 2017.

[95] Steven Wollkind, John Valasek, and Thomas R. Ioerger. Automated conflict resolution for air traffic management using cooperative multiagent negotiation. In *Collection of Technical Papers - AIAA Guidance, Navigation, and Control Conference*, 2004.

[96] Thomas H. Kosel. Computational techniques for stereographic projection. *Journal of Materials Science*, 1984.

[97] Leonhard Euler and Scott L Hecht. *Elements of Algebra*. CreateSpace Independent Publishing Platform, 2015.

[98] Mark De Berg, Otfried Cheong, Marc Van Kreveld, and Mark Overmars. *Computational geometry: Algorithms and applications*. 2008.

[99] Pei-jun Du, Tao Fang, Hong Tang, and Peng-fei Shi. Encoding methods of spectral vector in hyperspectral romote sensing image. *Journal of Shanghai University (English Edition)*, 9(1):52–57, Feb 2005.

[100] Autonomous University of Barcelona, Cranfield University, ASLOGIC, and ENAC. PARTAKE. http://www.partake-aero.eu/. Accessed: 2020-05-03.

[101] Autonomous University of Barcelona, Cranfield University, ASLOGIC, and Technische Universitat Braunschweig. AGENT. http://www.agent-aero.eu/. Accessed: 2020-05-03.

[102] Nina Schefers, Juan José Ramos González, Pau Folch, and José Luis Munoz-Gamarra. A constraint programming model with time uncertainty for cooperative flight departures. *Transportation Research Part C: Emerging Technologies*, 96:170–191, 2018.

[103] Thomas H Cormen, Charles E Leiserson, and Ronald L Rivest. *Introduction to Algorithms , Second Edition*. 2001.

[104] P. Faratin, C. Sierra, and N. R. Jennings. Using similarity criteria to make issue trade-offs in automated negotiations. *Artificial Intelligence*, 2002.

[105] Tim Baarslag, Michael Kaisers, Enrico H. Gerding, Catholijn M. Jonker, and Jonathan Gratch. Computers That Negotiate on Our Behalf: Major Challenges for Self-sufficient, Self-directed, and Interdependent Negotiating Agents. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2017.

[106] Reyhan Aydoğan, Tim Baarslag, Koen V. Hindriks, Catholijn M. Jonker, and Pınar Yolum. Heuristics for using CP-nets in utility-based negotiation without knowing utilities. *Knowledge and Information Systems*, 2015.

[107] Luis Delgado and Xavier Prats. En route speed reduction concept for absorbing air traffic flow management delays. *Journal of Aircraft*, 49(1):214–224, jan 2012.

[108] Ivan Marsa-Maestre, Mark Klein, Catholijn M. Jonker, and Reyhan Aydoğan. From problems to protocols: Towards a negotiation handbook. *Decision Support Systems*, 2014.

[109] Jacco M. Hoekstra and Joost Ellerbroek. BlueSky ATC simulator project: an open-data and open-source approach. In *Proceedings of the 7th International Conference on Research in Air Transportation*, pages 1–8, Philadelphia, 2016.

[110] Raz Lin, Sarit Kraus, Tim Baarslag, Dmytro Tykhonov, Koen Hindriks, and Catholijn M. Jonker. Genius: An integrated environment for supporting the design of generic automated negotiators. *Computational Intelligence*, 2014.

[111] R E Klomp, R Riegman, C Borst, M Mulder, and M M Van Paassen. Solution Space Concept : Human-Machine Interface for 4D Trajectory Management. In *Thirteenth USA/Europe Air Traffic Management Research and Development Seminar*, 2019.

[112] COTTON team. Innovative complexity and workload assessment to support future Capacity Management processes in TBO. Technical report, 2019.

[113] Shai Shalev-Shwartz and Shai Ben-David. *Understanding machine learning: From theory to algorithms*. 2013.

[114] Thomas R. Gruber. Toward principles for the design of ontologies used for knowledge sharing. *International Journal of Human - Computer Studies*, 43(5-6), 1995.

[115] Michael Genesereth and Nils John Nilsson. *Logical foundations of artificial intelligence*. 1987.

[116] Vu Duong, Gilles Gawinowski, Jean-Pierre Nicolaon, and Darren Smith. Sector-Less Air Traffic Management. *4 th USA / Europe Air Traffic Management R&D Seminar, Santa Fe, New Mexico*, 2001.

[117] Ana P. G. Martins, Tobias Finck, Vilmar Mollwitz, Fanni Kling, and Dániel Rohács. Feasibility study of Flight Centric Mode of Operations. In *SIDS2019*, 2019.

[118] CORUS Consortium. CORUS Enhanced Overview. Technical report, 2019.

[119] Cristina Barrado, Mario Boyero, Luigi Brucculeri, Giancarlo Ferrara, Andrew Hately, Peter Hullah, David Martin-Marrero, Enric Pastor, Anthony Peter Rushton, and Andreas Volkert. U-Space Concept of Operations: A Key Enabler for Opening Airspace to Emerging Low-Altitude Operations. *Aerospace*, 7(3):24, mar 2020.

[120] NASA. NASA Embraces Urban Air Mobility, Calls for Market Study. https://www.nasa.gov/aero/nasa-embraces-urban-air-mobility/, 2017. Accessed: 2020-05-03.

[121] Airbus. Urban Air Mobility - the sky is yours. https://www.airbus.com/newsroom/stories/urban-air-mobility-the-sky-is-yours.html, 2018. Accessed: 2020-05-03.

[122] Uber. Uber Elevate - The Future Of Urban Air Transport. https://www.uber.com/es/es-es/elevate/, 2016. Accessed: 2020-05-03.

[123] Airbus. Airbus UTM. https://www.airbusutm.com/. Accessed: 2020-05-03.