Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management

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CERTIFICA

Que la tesis doctoral titulada "Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management" por Sergio Ruiz Navarro, presentada como parte de los requerimientos para la obtención del Título de Doctor en Telecomunicaciones e Ingeniería de Sistemas, se ha desarrollado y redactado bajo su supervisión.

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Dr. Miquel Àngel Piera Eroles

Barcelona, 12th September 2013

Prologue

Motivation

Currently the European Union is financing important investments in R&D in order to strategically foster the Single European Sky. Through EUROCONTROL (the organization in charge of the safety along the European airspace), the European Union has been able to bring the main research groups and airspace stakeholders into the picture in order to define the main roadmaps of the future European air traffic system. Such a project for the modernization of the European sky is named SESAR (Single European Sky ATM Research).

Universidad Autónoma de Barcelona has been collaborating directly with some EUROCONTROL technological partners that are involved in different research projects related to SESAR, partners such as ATOS Origin, INDRA, ALG-INDRA and Boeing Research and Technology Europe (BR&TE). The present dissertation is the result of some of these collaborated projects, such as the project ATLANTIDA (a project leaded by BR&TE aiming at exploring the full automation of air navigation and traffic management procedures in the context of a potential future ATM concept) and the SESAR WP-E project STREAM (a project leaded by ALG-INDRA aiming at exploring strategic de-confliction algorithms for a large amount of trajectories).

Under the supervision and direction of Dr. M.A. Piera, the present research has been focused on the design and implementation of Decision Support Tools to improve some of the decision-making processes related to Air Traffic Management, considering the use of 4D trajectories along the entire European airspace. Specifically, a **Conflict Detection and Resolution system for Strategic De-confliction** has been designed and implemented in this research, which has been a fundamental part of the system proposed by the STREAM project (see Section 1.6 and Chapter 3).

On the other hand, this dissertation has been written down with the intention to qualify and pass the requirements of the PhD programme in Telecommunications and Systems Engineering of the Universidad Autónoma de Barcelona. Thus, a compendium of five articles that have been published in relevant journals and congresses of the research field has been attached and constitute the core of this dissertation.

For the development of this research a deep and exhaustive literature review has been conducted, in addition to the contributions and insights provided specially by BR&TE and ALG-INDRA during internal project meetings, as well as direct consultations to experimented air controllers and pilots from recognized organizations (EUROCONTROL, AENA, Air Europa…) also involved in the development of the SESAR project.

The feedback obtained from the project reviewers (especially during scheduled and informal meetings with STREAM project supervisors form EUROCONTROL) has also became an important source of knowledge, together with the feedback obtained from the referees of several international journals and congresses of the aeronautical field to which selected partial pieces of this research were gradually sent with the most updated findings. Thanks to theses formal reviews (and also to more informal talks happened during the networking opportunities in congresses) a lot of high-quality information could be obtained, thus allowing the research being refined while making steps forward. Those journals were IEEE Intelligent Transportation Systems, Elsevier Transportation Research: part C and Journal of Aerospace Operations, among others, and the congresses were UAV'09 (Reno, US), the Boeing CDA Procedures'09 (Barcelona, Spain), the NAV'09 (London, UK), the WAMS'10 (Búzios, Brazil), the ICRAT'10 (Budapest, Hungría) where a ***best paper award*** was granted, the ATACCS'11 (Barcelona, Spain), the ATM Seminar'11 (Berlin, Germany) (only assistance, no publication), the SID'11 (Toulouse, France), the ICRAT'12 (Berkley, US) and the SID'12 (Braunschweig, Germany) where the ***SESAR Young Scientist Award 2012*** was granted (see Appendix B).

Acknowledgements

The publication of this dissertation would have not been possible without the collaboration and support of many persons. In the first place I would like to grant part of the credit to the director of the research, Dr. Miquel Àngel Piera, who proposed the fields and topics of the research, and who contributed with many ideas and rigorously reviewed this dissertation. In addition, he established most of the relevant contacts with different international organizations that were crucial for the right development of the research. He has been also aware of the international events and congresses of recognized prestige in the field, which allowed sharing

and discussing the most updated findings and developments achieved during the research with the best ATM scientists and professionals around the world.

On the other hand, I would like also to thank to Rubén Martínez from ALG-INDRA who gave us the opportunity to link our research with a project sponsored by EUROCONTROL (i.e., the STREAM project). Also many thanks to all his team, especially to Andrea Ranieri and Alex Corbacho, who have actively participated throughout the entire STREAM project duration and contributed to the orientation and development of this research with their deep knowledge in ATM consultancy.

I extend my gratitude to Miguel Vilaplana, Javier López, Isabel del Pozo and Johan de Prins, among other staff working at the Boieing Reseach and Technology Europe (BR&TE) centre, located in Madrid. All of them have contributed with ideas, classified information (such as the actual optimal trajectory profiles of some aircraft models), the construction of some of the traffic scenarios used in the simulations of this research and with the Trajectory Predictor tool that "flew" the trajectories of the worked scenarios taking into consideration realistic aircraft performances.

Of course, I would like to be grateful with the project reviewers of EUROCONTROL, especially to Colin Meckiff, Leila Zerrouki and Jean-Luc Marchan, who kindly listened and discussed our new ATM concepts and many times suggested changes and indentified areas of improvement to adapt our proposals to the actual needs of the airspace and also to ease the transition towards the SESAR ATM concept.

Also the anonymous reviewers of the journals and congresses deserve part of the credit of this dissertation, since with their feedback they notably contribute to improve the quality of the written articles and also of the entire research.

I would like also to appreciate the help given by some of my colleagues and friends: Jordi Manzano, captain of Air Europa that is very actively involved in the SESAR processes, thank you for contributing with the view of the pilots and for kindly answer all my questions about the current and future ATM systems. Thank you also to Jordi Jiménez and his team of programmers in CIMNE (Universidad Politécnica de Cataluña) as well as to Liana Napalkova and her team of programmers in ASLOGIC, who offered their help during those difficult moments in which a programmer leads with errors (sometimes esoteric) of any programming process. Many thanks to Jenaro Nosedal, Olatunde Baruwa, Mónica Gutierrez and Catya Zúñiga, colleagues at the Universidad Autónoma de Barcelona, for their contributions and help.

And of course I cannot forget to thank my parents for their financial, logistical and emotional aid given to me during all of these years and that made easier the achievement of my personal goals.

Executive Summary

Nowadays, due to the continuously growing demand of the air transportation in Europe, which facilitates fast and safe displacements, a high density of air traffic across the European airspace can be observed. Some sectors of the current European airspace can be notably congested in certain periods, and can be even fully saturated during most confluent peak hours. Some forecasts conducted by the European Union have predicted that the air traffic operations will be in the next decade the double of the current observed traffic volume, therefore the European Union has started a project (i.e., the SESAR project) to modernize the technology and procedures currently used by the air traffic management in order to increase the current airspace capacity (thus being able to allocate the expected future demand) as well as to improve the efficiency and coordination of all the operations.

As a technological contribution, this research project introduces a strategic de-confliction algorithm developed under the EUROCONTROL's STREAM project and launched under the umbrella of the Single European Sky ATM Research (SESAR) Programme. The underlying fundamental concept is to make use of the enriched information included in the flights prior to take-off and/or while the flights are airborne in order to allocate conflict-free routes/trajectories in a traffic-planning phase that, in the absence of flight and/or network uncertainties, should lead to an actual conflict-free scenario during the flight execution phase.

It is expected that the proposed approach could decrease the workload of the air traffic controllers, thus improving the Air Traffic Management (ATM) capacity while meeting the maximum possible expectations of the Airspace Users' requirements in terms of horizontal flight efficiency.

The main modules of the implemented system are presented in this dissertation, i.e., the conflict detection and the conflict resolution modules; these modules are designed to enable the processing of thousands of trajectories within a few seconds and encompass a global network scope with a planning horizon of approximately 2 to 3 hours.

The conflict detection (CD) module makes use of Spatial Data Structures as the vehicular technology to create an ATM micro-scale model framework in which it is possible to store and manage the precise micro-scale description of the overall 4D trajectories in the ATM system, thus potentially enabling a centralized and complete view of the current state-space of the system and its evolution along the time. This is a key contribution of this research since such micro-scale model framework provides with a global discrete event representation of the dynamic system, which is necessary for a better understanding of the complexities and emerging dynamics that cannot be understood without a global (4D/nD) perspective of the ATM system.

The conflict resolution (CR) module is divided into two sub-modules, the Resolution Trajectory Generator (RTG) that aims at providing feasible trajectories for each aircraft in conflict with a local optimization scope, and the Interaction Causal Solver (ICS) that applies a causal model for finding efficient network solutions with a global scope through the analysis of the emergent dynamics (i.e., domino effects). This architecture facilitates that the potential domino effects generated by the local trajectory amendments can be analysed during the entire flight routing allocation process and, at the end of the process, different conflict-free Pareto-efficient network scenarios can be identified. Various performance indicators can be taken into account in the multi-criteria optimization process, thus offering to the network manager a flexible tool for fostering a collaborative planning process.

The implementation of the system has been conducted in C++ with an Object Oriented approach, and several simulations using realistic scenarios (both with and without uncertainties) have been performed and analysed to verify the correct functioning of the concepts. Simulation results have shown that this strategic CD&R tool is excellent from the computational-efficiency point of view and that it is able to identify and manage the emergent dynamics of the system.

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Chapter 1

Introduction

For many years Europe has been involved in the unifying process of its foundational countries. For instance, in 1985 the European Single Market was created, a fact that supposed the actual elimination of the terrestrial borders and the free circulation of goods and persons. Later, in 1990, the Economic and Monetary Union was initiated, thus abolishing the economic and finantial frontiers and, consequently, allowing the free movement of capitals while some community organisms were founded to control the economic and monetary policies among all the involved countries in an unified way, upon the final adoption of a common currency, the Euro. It seems logical, therefore, considering this unifying framework of the European countries, that such dynamics shall also affect to the continental airspace management policies, which up to now they have been characterized by a big fragmentation, not only geographical (many airspace sectors), but also technological (non-integrated information systems) and legislative (with many particular laws for each of the countries).

1.1 The Single European Sky

In 2001 the European Commission decided to start the process of eliminating the airspace borders, with the intention of organizing and managing the European airspace and the air navigation in an allied way, thus conceiving what is known as the Single European Sky. This process, which is still alive and not expected to end up to at least 2030, will bring the total modernization of the technologies and procedures used to manage the air traffic in Europe.

The current Air Traffic Management (ATM) model is based on a largely fragmented and sectored management of the air traffic flows, and thus it is not matching the airspace requirements that come along with the new unifying process of the sky management. Due to that, the European Commission requested to EURO-

CONTROL [18] the task of designing the future European ATM, with the purpose of adapting it to the new needs and opportunities of the Single European Sky.

It must be noted that, beyond the safety factors (that of course are considered a must-have for any ATM model), there are other performance factors evenly important that should be also considered in order to deliver a good design for the future ATM in Europe. Among these factors, three are especially important, and thus EUROCONTROL has to pay maximum attention to them, which are: the available airspace/ATM capacity, the cost-efficiency relationship of flight routes and procedures, and the environmental impact of the air transport.

With regards to the airspace/ATM capacity, it is convenient to point out the current situation. In last decades the air transportation system has experienced an important growth in the demand, probably due to factors such as the new intra-continental relationships (direct cause of the territorial, political and economical unification of the continent), together with the comfort, speed and safety that air transport currently offers for intercity and international journeys, as well as to the considerable fall of prices in the market since the introduction of the low-cost carriers. Altogether these factors have caused that from 2002 onwards the market has experienced a growth rate trend of 5% per year (except in 2008, 2009, 2012 and 2013 due to the economic crisis) [99, 34, 49, 46], which means that the European airspace must safely afford a huge amount of daily flights (nowadays around 30.000), with peaks of several thousands of aircraft flying over Europe at the same time (around 5000 simultaneous aircraft in the most demanded hours), and thus sometimes bringing many of the air sectors to their maximum capacity limits. On the other hand, some economic forecasts predict that the air transport demand could keep growing at same levels for at least the next two decades, thus a demand two times bigger is expected by 2030 [105, 30, 46, 31]. Therefore, the achievement of relevant improvements in the airspace/ATM capacity is a necessary condition and a key strategic goal for the successfulness of Single European Sky project.

On the other side, another important objective to reach with the introduction of the new European ATM model is the reduction of the costs and the augmentation of the system efficiency by improving the air routes available among airports and the manoeuvres and procedures executed by aircraft during all phases of flight. For that purpose it is important to take advantage of the new opportunities arising with the unification of skies, such as the economies of scales and synergies, and the potential synchronization of all the Single European Sky stakeholders.

Finally, another fundamental pillar of the incoming ATM paradigm is the minimization of the negative environmental impact of the air transportation system, which is a key strategy for the achievement of a sustainable economic and societal growth. Important reductions of the negative gas emissions (Greenhouse Effect contributors) can be expected thanks to the introduction of new route management strategies (e.g., dynamic free-route allocation) and new flight procedures (e.g., continuous climbing and descent operations), altogether with new advanced designs of aircraft fuselage and engines.

Note that all the aforementioned target factors (i.e., safety, capacity, cost-efficiency and environmental impact) are tightly coupled, thus actions driven to improve any of them may directly or indirectly affect the others (in a positive or a negative way). For instance, the introduction of the technological enablers that bring the free-route navigation available for the airspace users (i.e., more flexibility for the flight route planning, with only a few restrictions applied to ensure traffic separation and synchronization), will suppose an improvement for both the cost-efficiency and the environmental impact of the flights (i.e., more direct flights and less burned fuel), while at the same time it will allow an effective augmentation of capacity and safety, due to a more efficient utilization of airspace and a better synchronization of operations.

1.2 The SESAR Programme

The SESAR programme, whose acronym stands for *Single European Sky ATM Research*, aims at defining (with a high-level description) the technological and procedural requirements needed to build the project of the Single European Sky, as well as to coordinate the posterior development and deployment activities [99, 100, 101, 102, 103, 104, 105].

Currently, the Air Navigation Service Providers (ANSPs) in Europe and their corresponding Decision Support Tools (DSTs) are not efficiently integrated and are often based on technologies and procedures that are close to work at their maximum capacities. Some of these technologies have their origin 50 or 60 years ago (e.g., voice radiotelephony communications) and thus they were designed to respond to the needs of other ages and to work under scenarios with much less air traffic densities. Up to now controllers of the different European nations have been able to maintain a safely and orderly flow of air traffic across the continent. However, some of the controllers' decisions could be nowadays being over-conservative and inefficient due to the currently established decision support tools and traffic management procedures and protocols, which altogether are somehow old-fashioned. For instance, the traditional use of voice communications (i.e., analogic communications and phraseology) is still extensively used between pilot

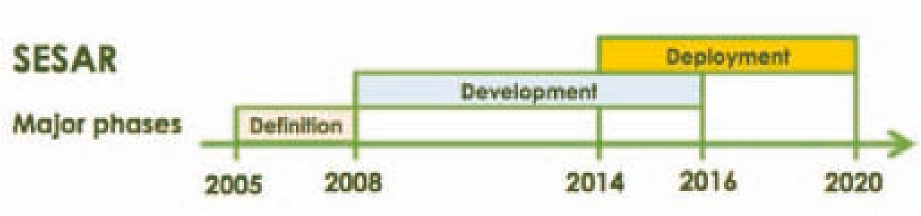

Figure 1.1: Major phases of SESAR programme

Figure reproduced from the SESAR documentation that shows the calendar of the major phases defined for the modernization of the European ATM, i.e., Definition, Development and Deployment.

and controllers, while the usage of data-link communications shall enable the introduction of more sophisticated and computerized DSTs (which usually are fed with digital data).

Therefore, the main goal of SESAR is to foster a complete modernization of the technologies that will give support to the future European ATM. And this is intended through the creation of the SESAR Joint Undertaking, an entity founded by the European Commission together with Eurocontrol with the purpose of joining and coordinating the most relevant European Union stakeholders, public and private, that may be willing to dedicate efforts to R&D in order to make the Single European Sky to come into a reality.

Three phases were planned for the initial execution of the SESAR programme (see Fig. 1.1). The first one was the Definition phase, from 2005 to 2008, which was leaded by EUROCONTROL and the European Commission. The second one, currently on going, is the Development phase, which is leaded by the SESAR Joint Undertaking [106] and is expected to finish around 2016. In 2014 is expected to start the Deployment phase, which will be mainly contributed through industry, and will last up to 2020 and beyond, the target date in which some important achievements of the Single European Sky shall be consolidated, such as the Trajectory Based Opereations (see Section 1.5). It shall be noted that the ATM System will further evolve after 2020 in order to address the total set of political and technological design goals defined for the Single European Sky.

Increasing the number of aircraft that can fly in the same time period (i.e., airspace capacity) is a major issue to be improved in the current European Air Traffic Management system, since the congestion of the most demanded en-route sectors and airports currently cause important unbalances between airspace/ATM demand and capacity. which are usually translated into departure and en-route delays that negatively impact on the flights punctuality and in turn generates collateral economical and societal costs of significant order [99, 101, 105].

Considering that it has been forecasted in Europe a likely increment of the air traffic flows in a factor of 2x or 3x by 2030 [46, 105, 31], it is clear the necessity of **finding new ways of increasing the airspace capacity while safely and efficiently managing a higher amount of flights**, by means of designing and developing **new Decision Support Tools** enabled by a technological upgrade of the Communication, Navigation and Surveillance technologies [22, 25, 30].

The solution proposed by the SESAR programme is a paradigm shift towards a new Concept of Operations [101, 105, 42, 47], which implies the evolution from the current ATM operations that are oriented to airspace and flows management (in which flights are regulated according to the actual airspace/ATM capacity available) to another ATM concept in which operations are oriented to trajectory management (in which the airspace resources are allocated according to the flight intentions/demand and preferences of the airspace users).

Section 1.3 presents a schematic picture of the current ATM, while Section 1.4 states the main shortages and improvement areas observed during the analysis of the current ATM. As it is argued in those chapters, the four major shortages and improvement areas identified in the current ATM system are, first, the lack of proper coordination between the network/flows planning and the air traffic control procedures applied at local level, second, the lack of flexibility to dynamically re-planning the airspace resources and flight routes at the moment of flight execution, third, the little automation aid during the decision-making processes, and fourth, the lack of a common traffic micro-model framework that allow the different stakeholders' DSTs to have a same view of the traffic situation as well as to anticipate the potential emergent dynamics caused by the local decisions in the system.

Section 1.5 summarizes the new concept of operations proposed by SESAR, which is oriented to the management of 4D trajectories. Section 1.6 introduces the project STREAM, a SESAR WP-E project for long-term innovation and research that is compatible with the SESAR target paradigm and that proposes a strategic Conflict and Resolution system to integrate and improve the relationship between the network and flight planning global decisions and the air traffic control local decisions. Section 1.7 describes the objectives and structure of this dissertation.

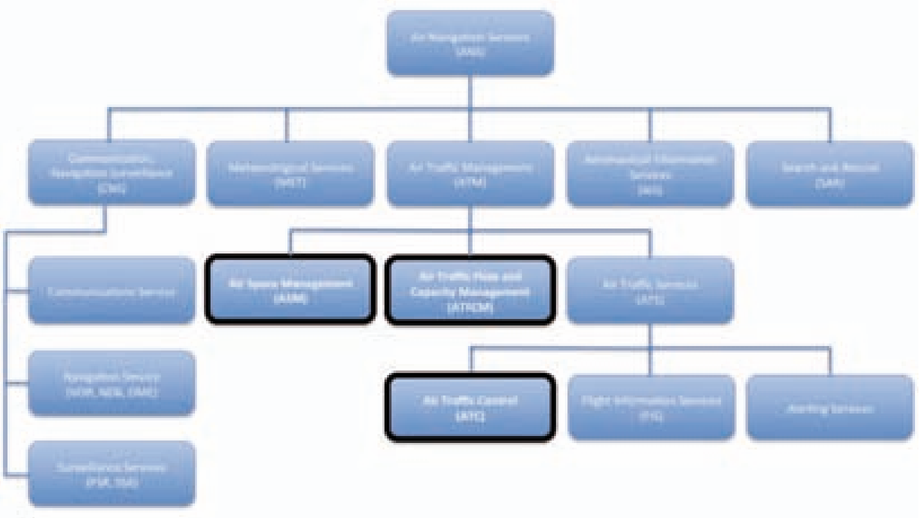

Figure 1.2: Scheme of Air Navigation Services (ANS).

Figure elaborated according to the source ICAO doc 9082. Three basic air traffic management layers are present (highlighted in bold), the ASM (long-term strategic phase), the ATFCM (strategic/pre-tactical and tactical phase) and the ATC (execution phase).

1.3 The Current ATM System: Airspace and Flows Oriented

The ATM aims at ensuring the safe and efficient flow of air traffic, based on the technological capabilities (and limitations) of the Communication, Navigation and Surveillance systems (CNS) and Meteorological services (MET) services available. Related ATM services encompasses different planning decision-making phases, such as the strategic Air Space organization and Management (ASM), the strategic, pre-tactical and tactical Air Traffic Flow and Capacity Management (ATFCM) services, and the tactical decision-making of Air Traffic Control (ATC) provided to every single flight during the execution phase. Figure 1.2 shows the basic scheme of Air Navigation Services, and in bold are highlighted the three mentioned decision-making related services [4, 58, 59]:

ASM service: is in charge of the planning and publishing of the civil and military air routes, the air sectors and the reserved areas, altogether by making use of the information derived from long-term demand and capacity predictions (e.g., one year look-ahead).

- The resulting airspace configuration (i.e., the available airways and sectors), together with the available ground infrastructures (i.e., airports, navaids, ATC Officers. . .) determines the –maximum– airspace ATM supply/capacity at the day of operations.

- Airlines make use of the (fixed) routes network published by ASM to issue their Filled Flight Plans (FPLs) several days –even months– in advance, which express the expected demand of the airspace infrastructures (i.e., airways, sectors, airports. . .) and ATM services at day of operations.

ATFCM service: is established to utilize the European airspace capacity to the maximum extent possible, while enabling safe, orderly and expeditious *Traffic Flows*[1]. The current ATFCM authority in Europe is EUROCONTROL CFMU (which will act as Network Manager in the future ATM system).

- The main goal of this service is to ensure that supply and demand match in order to avoid (unsafe) overloaded sectors at any time, i.e. Demand and Capacity Balancing (DCB), performed at the *day of operations D*.
- ATFCM makes a prediction of the airspace demand by computing (through roughly accurate models) the expected trajectories and their evolution over the time from the information of each individual FPL. Also from the pre-declared information of the ATC operators it is possible to anticipate the available capacity of every airspace sector. Those predictions are refined as the day of operations becomes closer, since the quantity and quality of information used for predictions usually increases.
- ATFCM presents 3 levels of decision-making actions, i.e. strategic (from 1 year up to 1 week before the *day of operations D*), pre-tactical (from 1 week to 1 day before D) and tactical (during all day D).
- In case that any imbalance is detected at day of operations D between the predicted traffic and the available network capacity, the ATFCM shall apply *regulations*[2] to some selected flights (usually delays but also re-routings and flight level changes).
- ATFCM decisions are made using aggregated airspace demand models (i.e., Traffic Flows) with the purpose of not oversaturating the pre-declared capacity of any sector. However, decisions made over individual flights dur-

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[1] A *Traffic Flow* is composed by several flights moving through a given airspace region at a given time period and in a common direction

[2] A *regulation* is a method of matching traffic demand to available capacity by limiting the number of flights planned to enter in a given airspace or aerodrome, and it is achieved by issuing new departure slots and/or new routes to selected specific flights.

ing flight execution are delegated to the ATC services of each specific airspace sector. Therefore, the ATFCM actions do not ensure traffic separation/synchronization at individual flight level, neither there is a precise insight of how ATFCM decisions impact over the ATC sectors workload.

ATC service: is provided by the different ANSPs for the purpose of *guiding and facilitating the navigation* of each individual aircraft through the different airspace sectors while *preserving safety distances* among all aircraft during the flight execution.

- The ATC service is provided to each individual flight by different Air Traffic Control Officers (ATCOs) during all the execution phases of a particular flight, i.e. take-off, climbing, cruise/en-route, descent/approach, landing and taxiing [4, 58, 59, 57].
- Each of the ATCOs provides assistance to different flights crossing their assigned ATC sectors (i.e., with a local/specialized sector view).
- To preserve the safety distances among the traffic, the ATCOs are in charge of the tactical management of *conflicts* (i.e., predicted loss of minimum separation between two or more aircraft), also called *interactions* [58], and give instructions to pilots whenever necessary to modify their trajectories within the local sector.
- ATCOs of different ANSPs may use different technologies and DSTs to assist the traffic in the sectors under their responsability.
- Conflict Detection and Resolution (CD&R) processes for tactical planning purposes are currently executed with a look-ahead time typically limited to a maximum of 20 minutes (i.e., tactical applications) and with no global ATM perspective of how the decisions made at local/sector level may affect the rest of the network, i.e. considering the traffic only at local airspace-sector level and with little or none coordination with other downstream sectors. In other words, ATC decisions are made with no regards of the potential ATM system *emergent dynamics/domino effects* [69, 61].
- ATCOs tasks currently are highly human-dependent. In recent times, some automated tools have been developed to assist ATC during the tactical conflict management, like Medium Term Conflict Detection (MTCD) decision support tools (FASTI, iFACTS, ERATO or VAFORIT, among others [27, 23, 26, 35, 86]), or the early operational automated Conflict Resolution (CR) [28, 108, 74]. However, in all cases the CD&R processes (automated or not) are making decisions with a local specialized view of the traffic crossing a specific sector and with little or none coordination with other downstream

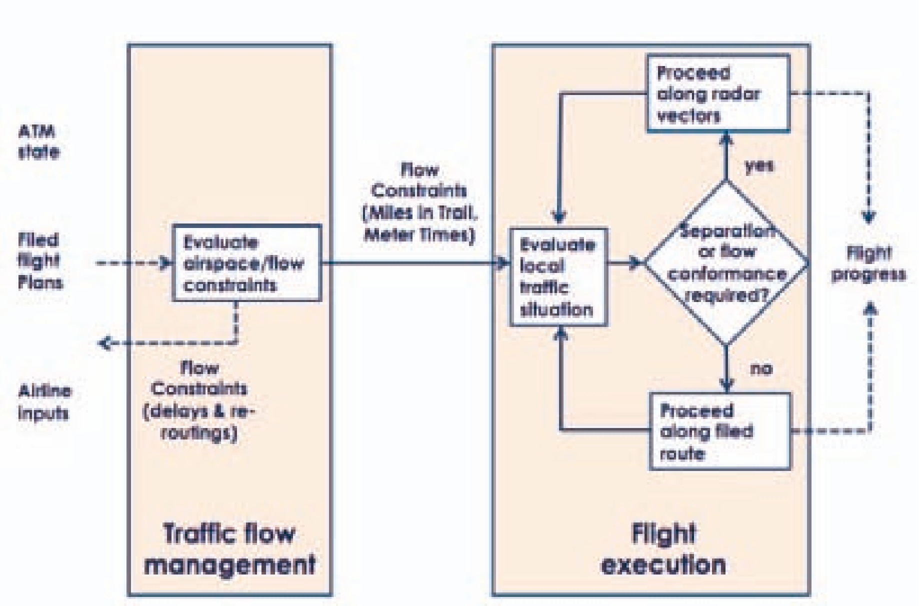

Figure 1.3: Simplified representation of the current ATM system

The focus of the current ATM is on avoiding any ATC sector oversaturaion to ensure the safe aircraft separation; little negociation opportunities are available for the airlines to re-plan their fligths in response to the changing constraints of the network.

sectors about how the local decisions mutuallly affect each other and the rest of the network.

Figure 1.3 illustrates a simplified conceptual representation of the current ATM system [85], in which the ATFCM evaluates the inputs received (i.e., current airspace capacity state, information from the FPLs and other inputs about the current state and intentions of the airlines) in order to predict the future *airspace demand,* with a look-ahead that comprehends from several hours up to some minutes before flight execution, and apply regulations when needed, i.e. *Flow Constraints.*

When the flights are in the execution phase, the air traffic controllers evaluate the *local traffic situation* within their sector and then determine whether each individual flight is separated sufficiently from the other traffic and also whether the flow restrictions are met. If an action has to be taken to maintain the required separation or to achieve the flow conformance (ATFCM actions do not ensure traffic separation/synchronization at individual level), the air traffic controllers typically issue tactical heading, altitude, or speed changes to the aircraft, which are often referred to as *radar vectors*. Note that these ATC actions, due to their sector-specialized ATM view, do not consider potential downstream traffic interactions and/or de-synchronization. If no controller intervention is required, the flights proceed along their filled routings (but still with no care about traffic synchronization at other sectors). Note that in this (simplified) ATM model the *flight planning* is conducted by the airlines off-line and prior to the execution phase and expressed through the FPLs. Thus, under this framework there is little flexibility (almost null) on either re-planning a flight or reconfiguring the airspace structure (e.g., routes) during the tactical ATFCM and/or the ATC procedures at execution phase.

1.4 The Current ATM Shortages and Improvement Areas

After analysing the current ATM organization the following shortages and potential improvement areas have been identified:

- **Lack of ATCFM and ATC integration:** network capacity and demand are balanced through macro-scale models (i.e., Traffic Flows) in which the pre-declared capacities of the ATC sectors (in terms of maximum number of aircraft per hour within an airspace sector) are taken into account by the ATFCM to issue “regulations” (i.e., delays and/or re-routings) in order to avoid the oversaturation of those sectors, while trying to keep the average delay at the lowest possible. However, during the ATFCM decision-making processes no impact assessment is considered of how the network/flow decisions affect to the real/actual micro-scale traffic pattern characteristics at each ATC sector. On the other side, the ATC decisions are made on the basis of particular micro-scale/trajectory models, but also with no impact assessment of the potential emergent dynamics/domino effects occurring at other sectors or at network/flow level. Therefore, this lack of integration between the ATFCM and ATC procedures during the execution phase currently causes poor traffic predictions and high uncertainty on the traffic evolution (i.e., traffic desynchronization), thus increasing the number and duration of flight delays as well as the ATC workload (due to the frequent separation tasks) across the network.

- **Lack of flexibility for a better planning/re-planning of both the airspace and the flights during the execution phase:** the actual evolution of traffic during the execution phase is often significantly different with respect to the planned one. For instance, if the capacity of a sector is predicted to be overloaded, the air traffic flow management issues time constraints on the take-off of some selected flights, i.e. new ATFCM departure slots, that are intended to modify the temporal airspace demand path of flights in order to comply with the available capacity at airports and at airspace sectors. However, the ATFCM slots introduce delays to the flights that generate important economic and societal costs, so during the execution phase it would be desirable to re-plan the airspace structure (e.g., airspace routes, ATC resources, among others) to increase capacity and mitigate delays, ot to re-plan the flights in order to optimize them at the maximum extent possible according to the business logics of the AUs. The lack of proper mechanisms for the coordination among ATCFM, ATC and AUs impedes the efficient dynamic planning in real-time in which refers to the airspace routes and resources available and also to the flight routes prefered by the airlines.

- **Little automation of some ATM procedures:** the current ATM system heavily relies on the skills of air traffic controllers and traffic flow managers. Most of the short term and medium term predictions are made by controllers and flow managers looking at air traffic displays and mentally extrapolating the situation, thus using little automation aid during the decision-making processes. In recent years there has been a considerable amount of works done to generate new Decision Support Tools (DSTs) for the automation of some ATM tasks, such as Medium Term Conflict Detection and Resolution (MTCD&R) [35], Arrival/Departure Manager (AMAN/DMAN) [84], Short Term Conflict Alert (SCTA) [33], among others. However, they still rely on different particular non-coordinated subjective view of the ATM (i.e., a local specialized view and a limited working look-ahead horizon) during the decision-making process and thus they cannot be properly coordinated with the rest of the ATM stakeholders' DSTs.

- **Lack of a common and global traffic model framework to integrate different DSTs:** the current ATM involves multiple decision makers that nowadays cannot be properly coordinated among the different sectors [71]. The complex ATM emergent dynamics appearing during local decision-making processes require a micro-level traffic description of the flights together with a global network perspective about the current and future ATM states in which the intentions of each individual stakeholder are considered. This is particularly true during the flight planning and execution phases if the goal of the ATM is to increase the predictability and efficiency of flights while reducing the total number of tactical –reactive– interventions (thus, increasing ATM capacity) along the air traffic system [71, 61, 69]. However, the current system is focused on ensuring the due separation between aircraft within a well structured local traffic problem, but with an incomplete picture of the overall ATM current and predicted states: from the ATCFM side, macro-scope/flow models are used rather than micro-scope/trajectory models, whereas from the ATCOs side there is a narrowed sector-specialized

ATM view with no visibility of the potential downstream emergent dynamics. One example can be found in the tactical conflict resolution procedures of ATC that do not consider the emergent dynamics/domino effects of a trajectory resolution maneuver downstream in other sectors.

With the separation management as the primary objective, the **current ATM system has to be considered safe but inefficient**, i.e. the current procedures used to manage the air traffic flows without considering the single flight trajectories across sectors, combined with the high volume of air traffic observed in Europe, actually causes the **saturation of several air sectors during the most confluent hours, thus strongly limiting the ATM capacity and causing important economic, environmental and societal costs** [30, 78, 105]. See Fig. 1.4.

These capacity problems are currently especially severe in Terminal Manoeuvring Area (TMA) sectors, particularly in those TMAs at where the most demanded airports are located and in which the number of flights and trajectory interactions are relatively high (i.e., high-complexity terminal operations). The congestion of such sectors derives in **frequent and long-duration airborne *holding procedures* nearby the airports** (a predetermined manoeuvre which keeps an aircraft within a specified airspace while awaiting for further clearance), which results on important extra fuel consumption and pollution [103, 78]. In addition, both the take-off delays (often imposed by ATFCM) and the en-route delays (often consequence of ATC radar vectors and/or flight navigation imprecisions) may be affecting to landing operations, thus causing **a trajectory de-synchronization that quickly may propagate to surrounding feeder sectors and may also affect to other TMAs and to the entire en-route airspace** (TMAs are currently considered one of the main bottlenecks of the ATM system due the strong negative effects that trajectory de-synchronization causes on the traffic converging to runways) [80, 30].

Therefore, as a conclusion of the analysis of ATM shortages and potential improvements areas it can be stated that, in order to noticeably improve the current ATM system, it is necessary a proper integration between the ATFCM and ATC procedures, while having the stakeholders airspace demands as a priority during the pre-departure and execution phases of flight. It is expected that further research in the following points could contribute to achieve such requirements:

- **A microscopic 4D trajectory model of the traffic flows**, i.e. a precise 4D micro-scale description of all expected/planned flights crossing the European airspace would be necessary to consider the complete expected/planned trajectory in a precise way from the entry point up to the exit point of the flight in the airspace under consideration (from gate to gate in

Figure 1.4: Complex air traffic flows through European ATM route network

The high volume and complexity of the air traffic observed in Europe actually causes the saturation of several air sectors during the most confluent hours; such ATM capacity limitations often cause delays and re-routes that bring important economic, environmental and societal costs as a consequence.

case of intra-European flights).

- **Automated and coordinated stakeholders' DSTs to ensure a more precise and stable traffic synchronization along the network**, thus contributing to more efficient and complex local-specialized decision-making responding to different ATM stakeholders and network needs. Note that the usage of digital data for automated DSTs may potentially enable an efficient data exchange and coordination between the different DST applications.

- **Allow the participation of the Airspace Users through arbitrated negotiation processes during the entire network planning process**, which would lead to a more efficient utilization of the airspace capacity and also to more efficient flight plans.

- **A common overall sight of the ATM current and predicted states**, i.e. the same view of the actual ATM capacity and predicted airspace demand would be necessary in order to allow a proper coordination between the different DSTs.

- **The anticipation of the potential emergent dynamics at the network due to local decisions shared among all the ATM stakeholders DSTs**, a concept that might improve the synchronization of all stakeholders procedures and that only can be achieved through the proper (digital) *information sharing* among all the agents, together with a network analysis tool able of providing the information of the expected emergent dynamics. A common information framework to share the current and predicted ATM states among all the stakeholders is also needed.

1.5 The Future SESAR ATM: Trajectory Oriented

1.5.1 The Trajectory Management Concept

The ATM model proposed by SESAR introduces the concept of "Business Trajectory" (or "Mission Trajectory" for military aviation), which constitutes the fundamental piece to be able of representing the air traffic flows with a precise 4D micro-scale representation.

Therefore, the *Business Trajectory* (BT) requires a precise definition in its 4 dimensions (i.e., 3 spatial dimensions and time), that is the reason why sometimes its name is substituted in the context of SESAR by the term "4D Trajectory". See Fig. 1.5.

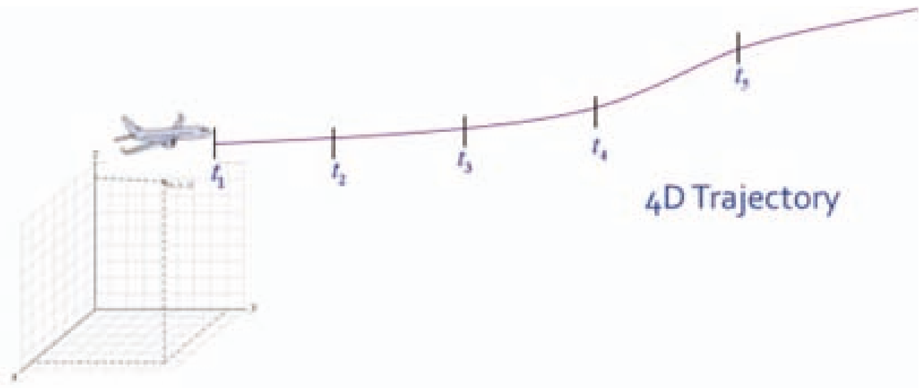

Figure 1.5: 4D Trajectory

The 4D trajectories are completely defined in the three spatial dimensions and in time.

At a first step, the BTs will be internally generated by the Airspace Users (AUs) (e.g.,, airline operators) even years before of the day of operations based on their business planning goals. At this stage the BTs are called *Business Development Trajectories* (BDTs) and they might not be shared with the rest of the ATM community.

However, the final execution of a BT requires that all stakeholders, including the airlines, the ANSPs and the airport providers, agree in a collaborative negotiation process the optimal gate-to-gate flight plan for each of the scheduled flights.

Thus, during this negotiation process among airlines, airports and controllers, the Business Trajectory receives the name of *Shared Business Trajectory* (SBT). In this process, the airline will propose a trajectory that best fits its business needs to cover the distance between two airports. Then, the different ANSPs will accept or deny the trajectory according to the airspace and airports restrictions. This process will be iteratively repeated until an agreement is reached among all the agents (i.e., a good-enough feasible trajectory is found), except in time-critical situations in which the ANSPs or the Network Manager (NM) may impose their trajectories.

Once all the stakeholders accept a SBT, and few minutes before to the take-off[3], its name comes out to *Reference Business Trajectory* (RBT). From this moment on, this trajectory will be considered to be the optimal one for that particular flight, since it takes into account all the controllers and airspace restrictions as well as the airlines preferences (it is assumed that airlines will optimize their

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[3] For instance during push-back since then the take-off time is often known with high accuracy.

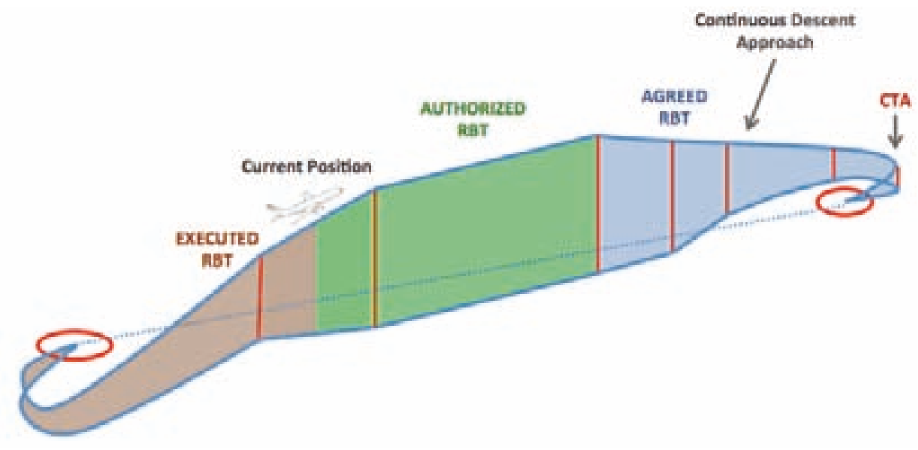

Figure 1.6: The unique description of the 4D Trajectory

The Business Trajectory will be considered from gate to gate during development, negotiation and acceptance and it will be cleared/authorized stretch by stretch (of certain duration each) during the execution phase.

trajectories at maximum extent according to their business logic).

At the moment of flight execution, the pilots must follow the RBT, with the help of the proper advanced airborne navigation systems, and applying the due manoeuvre amendments when necessary to not come outside certain tolerances defined by the Trajectory Management Requirements (TMR) for each flight. If at any time an unforeseen event comes up, for example, a regulation at destination airport due to bad weather that causes a delay and thus requires a change in the optimal trajectory, the RBT can also be used as a reference to minimize such tactical trajectory changes with respect the optimal RBT.

Any new trajectory proposition, revision or update will be made in due consideration of the **complete trajectory** still to be flown and not only at sector level, taking due account of the wider impact on other flights' concerned trajectories as well as on the network operations (i.e., domino effects/emergent dynamics). Note that since RBT express the user preferences and network restrictions, unsolicited ATC proposals (e.g., direct routings) may not in fact be beneficial for the airspace users, whereas destabilizing network effects may additionally occur downstream.

The Business Trajectory will be considered as a whole (i.e., gate to gate) during the development, negotiation and acceptance but it will be cleared/authorized during the execution phase for time-windows of order of 20-30 minutes (i.e., tactical look-ahead). See Fig. 1.6.

On the other hand, note that the term 4D Trajectory also contemplates (according to SESAR definitions) other kind of trajectories, such as:

- **Planned:** properly called Business Trajectory (or Mission Trajectory if military) and potentially adopting different forms according to the time horizon (e.g., SBT or RBTs).
- **Predicted:** trajectory computed by a Trajectory Predictor (TP), which corresponds to *what the aircraft is expected to fly* (also with different prediction horizons, i.e., for near, medium term or for strategic planning purposes) and it is continuously updated during the flight execution by both on-board and on-ground systems.
- **Executed:** trajectory actually flown by aircraft.
- **Alternate:** used for “what if” purposes during the planning process, thus meaning that each aircraft/flight may have several potential trajectories for planning purposes (although only one will be executed).

1.5.2 Need for Modern Technologies

The new SESAR paradigm requires of the effective development and deployment of the necessary Communication, Navigation and Surveillance (CNS) as well as the proper improved Meteorology (MET) technologies that will give support to the whole ATM system in order to achieve the goals of maximizing capacity and safety while minimizing costs and environmental impact.

In its simplest form, the 2020 CNS baseline to support the new SESAR ATM paradigm can be characterized as follows:

- **Communication:** technologies (e.g., data-link, CPDLC, among others) that will enable improved voice communication*s* and *digital data exchanges* between service actors within the system, such as those necessary to support the *System Wide Information Management* (SWIM), a net-centric ATM intranet that will allow to share information from and among all the stakeholders, thus enabling a Collaborative Decision Making (CDM) philosophy.
- **Navigation:** technologies (e.g., GNSS, P-RNAV, among others) that will enable precise positioning, timing and guidance of the aircraft to support high-performance and efficient *4D trajectory operations* in all phases of flight, thus allowing the use of *Free-Routing* (i.e., *user-preferred routing*) whenever possible;

- **Surveillance:** technologies (e.g., ADS-B, ASAS, TCAS, among others) that will enable *precise monitoring of all the traffic* to assure safe and efficient operations, including enhanced Traffic Situational Awareness, *Airborne Separation Assurance System* (ASAS) and *Traffic Collision Avoidance System* (TCAS).
- **Meteorology:** technologies (e.g., ground, airborne and satellite sensors, improved prediction models, among others) that will enable *accurate and timely meteorological information* incorporated as an integrated component of the system to give support for all phases of flight and for the determination of the optimum route/trajectory for each flight in both the planning and execution phases.

These technologies will be gradually implemented thus facilitating the transition towards the SESAR target Operational Concept through three complementary Steps:

Step 1, "time-based operations" (approximately 2008-2013): focused on flight efficiency, predictability and the environment, the goal is a synchronized European ATM system. Main characteristics:

- Time prioritization for arrivals at airports is initiated;
- Data-link is widely used;
- Initial trajectory-based operations are deployed through the use of airborne-calculated trajectories in the ground systems (sent through data-link) and a controlled time of arrival (to sequence traffic and manage queues).

Step 2, "trajectory-based operations" (TBOs) (approximately 2013-2020): focused on flight efficiency, predictability, environment and capacity, the goal is a trajectory-based ATM system where partners optimize "business and mission trajectories" through common 4D trajectory information. Main characteristics:

- Initial 4D-based business/mission trajectory management
- System Wide Information Management (SWIM) fully functional
- Air/ground trajectory exchange to enable tactical planning and new separation modes (i.e., strategic de-confliction and self-separation). Allocating all SBTs and RBTs through a strategic conflict management action based on a Collaborative Flight Planning may contribute to a higher flight plan optimization (according to each AU different definitions of "optimality") while reducing the ATC workload (at least in which refers to tactical conflict management), thus augmenting the overall ATM capacity.

Step 3, “performance-based operations” (2020+): based on the same concepts of TBOs, the goal is the implementation of a European high-performance, integrated, network-centric, collaborative and seamless air/ground ATM system, thus not only focusing the system in the enhanced separation provision provided by TBOs, but also managing the overall system to conform with other higher-level performance objectives (e.g., taking into account equity and fairness criteria, and reaching a good trade-off between flexibility, efficiency and robustness).

1.5.3 Trajectory Based Operations

Based on the above 4D trajectory management principles, the so-called concept of Trajectory Based Operations (TBOs) assumes that the proper new CNS technologies will be available to support the due positioning and navigation precision requirements, a more flexible planning process of flight routes and trajectories, an improved information availability (quantity and quality) for all on-board and on-ground systems, and a fast and reliable transmission of such information among all the relevant systems.

The aiming of TBOs is to allow pilots, whenever possible, to follow trajectories close to the optimal fuel consumption (“optimal” according to a calculated *cost-index* that relates operational costs and fuel costs). In general, an optimal trajectory consists on a horizontal dimension (i.e., *track*) that follows the most direct route possible between two airports, although not always it follows the shortest distance (i.e., Great Circle) since the expected wind maps are also taken into account, e.g. a jet stream in the flight direction may imply longer distance but less time and/or fuel consumption [15]; also the service taxation to fly across sectors is taken into account in case that relevant differences are present among the different ANSPs (the service taxation is expected to be more homogeneous among all the sectors in the future SESAR ATM). In the vertical plane, the preferred profile usually consists on climbing manoeuvres that are executed with a uniform and smooth acceleration until the top optimal cruise flight level is reached. Note that for each flight plan and aircraft mass there is an optimum flight level that rise up as soon as the mass is lowering. Therefore, since mass is continuously lowering (i.e., fuel burn), the optimum vertical profile is a trajectory continuously climbing up to a maximum altitude (i.e., *Continous Climbing Departure* or CCD) in which a continuous descent is started (i.e., *Continous Descent Approach* or CDA), which is calculated to land at the destination airport with a certain glide slope (typically 3^{o} or 4^{o}), thus to be executed with idle throttle whenever possible and up to ground contact (see Fig. 1.7). In this way, if the optimal horizontal, vertical and speed profiles are applied, the aircraft will not be airborne longer

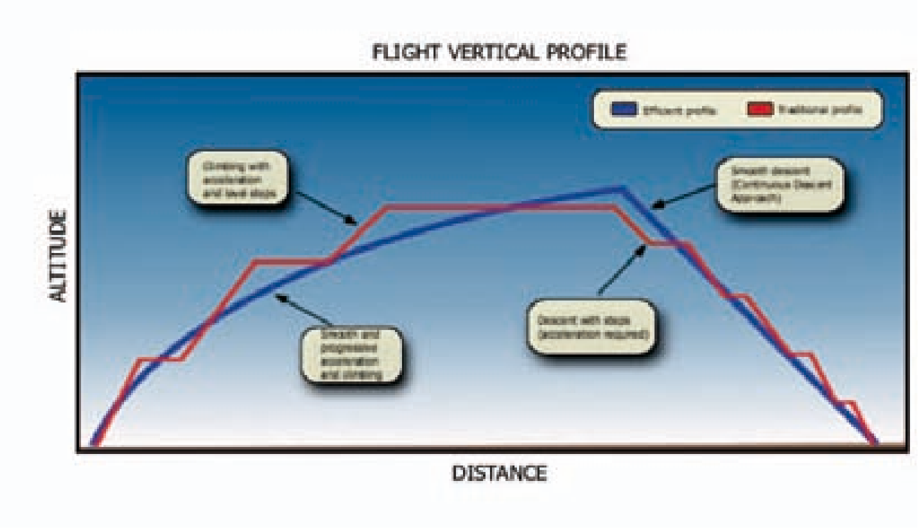

Figure 1.7: Differences between the *traditional* vertical profile and the ideal *efficient* profile

> *New flight procedures such as Continuous Climbing Departure (CCD) and Continuous Descent Approach (CDA) can potentially bring important fuel savings for the airspace users while reducing CO_2 emissions and noise around the airports.*

than necessary (which in turn implies more airspace capacity), while the smooth acceleration during the flight procedures may bring important fuel savings and a noticeable diminishing of the CO_2 emissions [78, 101, 47].

Note that in current ATM the optimal trajectory procedures are limited by several constraints, such as the pre-defined (and fixed) route structure, the semi-circular cruising level system[4] and the big amount of –not fully coordinated– sectors (in both the horizontal and vertical sky profiles). Therefore, one of the key aspects of the SESAR ATM concept is the simplification of the airspace structure, which conceptually will be divided into only two categories, i.e., the Managed and the Unmanaged airspace. The aiming of SESAR is to allow the management and utilisation of the airspace as a continuous mean (with as less restrictions as possible), so the planning and execution of trajectories can be as close to optimum as possible.

The Managed airspace will be dynamically configured according to the ex-

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[4] Current sky in Europe is divided in discrete layers called Flight Levels (FLs) separated 1000 feet from each other (Reduced Vertical Separation Minima applies). This is done to simplify the management of the air traffic while preserving the required levels of safety.

pected needs at each time of the planning look-ahead. During low/medium complexity operations, and whenever possible, it will be allowed in the SESAR ATM concept that aircraft fly the user-preferred routes (i.e., Free-Routes) across the en-route sectors, while in TMAs it will be possible to execute optimum (or close to optimum) vertical procedures, i.e., CCDs and CDAs.

When complexity will be temporarily high, the required capacity will be only achieved at the cost of some constraints on individual optimum trajectories, thus Free-Routing might be totally or partially suspended in high-complexity en-route areas and TMAs since some forcing 2D, 3D and/or 4D constraints will be issued through a Dynamic Route Allocation process that shall allow adapting the airspace traffic demand to the actual available capacity in real-time.

A Flexible Use of Airspace (FUA) will be also possible for coordinating civil and military operations, thus some airspace regions may be temporarily unavailable for civil flights, which together with the rest of the 4D network constraints (i.e., traffic synchronization measures) makes necessary a dynamic and collaborative ATM planning process.

1.5.4 The ATM Planning Process

In SESAR concept the planning at each point in time is represented in the Network Operations Plan (NOP), which facilitates the processes needed to reach agreement on airspace demand and capacity. It is supported by a set of collaborative applications that provide access to traffic demand, to airspace and airport capacities and to constraints and scenarios that assist in managing diverse events.

The airspace stakeholders will use the NOP as a single portal access to ATM information (e.g., demand and capacity situation). The ATM state-space information collection necessary for the ATM planning will be enabled by the modern CNS technologies applied at local level, whereas the distribution of the information among the stakeholders (i.e., *information sharing*) and the CDM approach will be enabled through the SWIM platform. See Fig. 1.8. The coordination of all stakeholders' DSTs (subject to the approval of the NM) is expected to bring an improvement of the cost-effectiveness per flight as well as a better utilization of the airspace capacity.

The NOP will be a dynamic rolling plan for continuous operations where:

- AUs declare their **trajectory intentions and preferences**
- ANSPs declare their **expected capacity** and resources

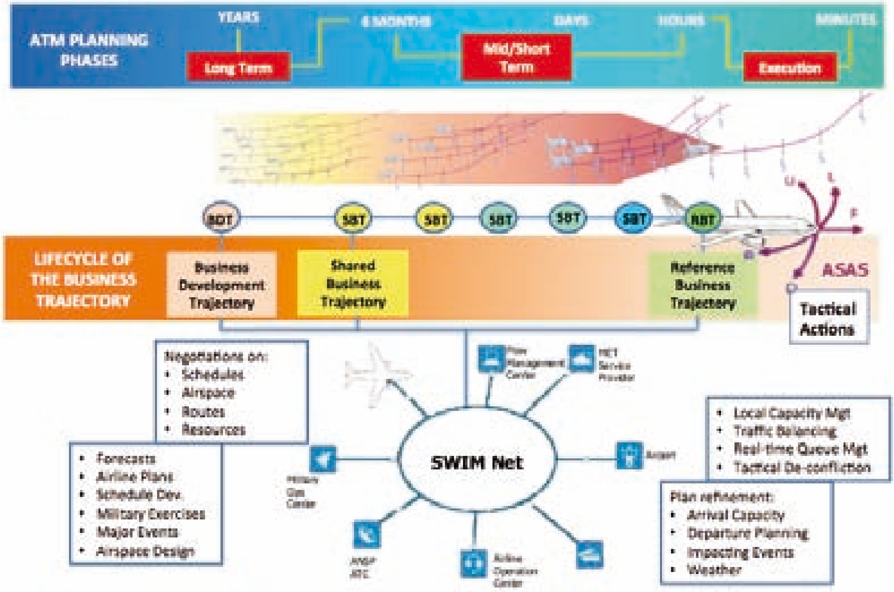

Figure 1.8: Collaborative Layered Planning

The Business Trajectory of a flight will evolve along different planning phases from the long term up to the execution phase. The planning and re-planning phases will be supported through a Collaborative Decision Making Process among all the ATM stakeholders enabled by SWIM network.

- NM facilitates dialogue to **resolve demand/capacity imbalances in a collaborative manner** (NM can impose decisions in case of no agreement reached in timely-critical situations).
- Agreements, trajectories and/or resources changes, and other **ATM data is publicly available** to all stakeholders.
- In case of sudden demand/capacity shortfall the NM initiates a **User Driven Prioritization Process (UDPP) allowing a resource trading among stakeholders** to self-solve the imbalance situation (NM will monitor the process to make sure that an acceptable solution is available in due time).
- **During execution phase the NOP continues** showing the most updated information

The Collaborative Decision Making to achieve a traffic Demand and Capacity Balancing can be schematized as follows (see also Fig. 1.8):

Long term planning:

- BDT is progressively enriched but not shared.

Medium and Short term planning:

- Published SBTs in the NOP express the users intentions.
- ANSPs provide with the information about the expected airspace capacities and potential constraints.
- NM analyses the network impact (i.e., emergent dynamics) of user intentions and facilitate collaborative planning to balance demand and capacity.
- Information quality increases (e.g., weather forecasts) near to the day of operations and thus the network planning is refined to ensure stability.
- A Strategic De-confliction process (ideally delivering conflict-free routes) applied to flights at pre-departure phase will reduce the need for tactical intervention at the execution phase.

Execution phase:

- RBTs are instantiated.
- In case of network disruptions (e.g., sudden loss of capacity in a sector or airport) the planning process respond rapidly to the changing situation.

- A Strategic De-confliction process (ideally delivering conflict-free routes) applied to airborne flights during the execution phase will reduce the need for downstream tactical intervention.

Note that an important enabler for the introduction of such a new ATM paradigm that relies on Trajectory Based Operations is to provide with a common modelling framework to store and share the same State-Space (SS)[5] information among all the stakeholders, thus enabling a common view of the ATM operations [71]. Note that a simplified 4D ATM model will be assumed in this dissertation, thus the SS information of interest will consist on the spatial definition of the nominal traffic trajectories together with the corresponding time-stamps (i.e., 4D Trajectories), with no consideration of other ATM aspects such as weather, ATC sector capacities, or ATM uncertainties, among others.

1.5.5 Conflict Management and Traffic Synchronization

The new advanced CNS groundside and airborne capabilities will enable the introduction of new separation modes (that will coexist with the traditional ones, i.e., the ATC tactical vectors and clearances), such as the strategic trajectory de-confliction and the aircraft self-separation, which may be used not only to ensure safe navigation but also to achieve the proper traffic synchronization when needed (in general along the entire airspace, but especially during high-complexity landing operations, in order to ensure the maximum utilization of the available airport/runway capacity).

The term *Strategic De-confliction* is often used to define actions taken when the SBT take-off time is known with sufficient accuracy (e.g., after *push-back*) or even after the flight is airborne, but always with sufficient time to allow a Collaborative Decision Making (i.e., Collaborative Flight Planning) process to occur. It excludes tactical instructions and clearances that need an immediate response, but includes activities such as dynamic route allocation [42, 47].

The use of strategic conflict management measures during the collaborative flight and ATM planning processes, together with more accurate flight navigation and trajectory predictions, will allow longer duration clearances, which in turn

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[5] By definition, the *state* of a dynamic system is the minimum amount of variables (called *state variables*) such that by knowing the current value of those variables and the future inputs to the system, it is possible to completely determine the evolution and values of the future states that the system can reach [70]. If n state variables are necessary to describe the system, then a *state vecto*r is a vector with n components (one for each state variable) whose values completely determine the state of a system at a certain time instant. Therefore, the SS of a system is an n-dimensional space in which each state variable can assume its domain values.

may notably reduce a portion of the ATCOs workload, thus increasing the ATM capacity and safety (i.e., less risk of collision). Therefore, moving from current short-term tactical instructions to more strategic 2D, 3D and 4D clearances (for suitable equipped aircraft) is a corner stone of the SESAR concept [42, 47, 101].

The new advanced navigation avionics allow implementing ASAS and TCAS, therefore in case of –slight– traffic de-synchronization (thus requiring separation measures) the pilots will be able to assume (by ATC delegation) the responsibility of separation and apply the necessary trajectory amendments. Automatic constant monitoring may trigger a RBT negotiation process if the execution of the trajectory amendments are predicted to negatively affect the previous Network Operations Plan. In addition, the future 4D-FMS avionics are expected to be able of working with Target Times (TTAs/TTOs) and Controlled Times (CTAs/CTOs) in order to ensure due synchronization, either for conflict dilution purposes or for efficient airspace resource utilization (especially of runways).

The initial traffic synchronisation of a flight will start as the destination airport initiates the negotiation of Target Times of Arrival (TTAs). Once agreed a TTA between the Airspace User and the Airport agents, the TTAs will be allocated and distributed by NM to all concerned actors through the NOP/SWIM. Since a TTA will not be compulsory (is a target), a tolerance will be associated to the TTA, thus in the execution phase the airline could change the RBT profile and therefore not to reach the TTA (it depends on Airline policy, e.g. economical speed versus higher speed to meet connecting flights).

After receiving clearance of the TTA from the NM and the Airport, the AU will update its preferred take off time (from trajectory backtracking), thus feeding the CDM process at the departure airport for the calculation of a Target Take-Off Time (TTOT). Note that current regulation of departure flights (i.e., CTOT) will not be necessary anymore if airports (and ATM in general) are operating normally.

An imposed time-constraint, i.e. Controlled Time of Arrival (CTA), with only few seconds of looseness, will be only used as an exception in relation to capacity constrained environments to ensure appropriate sequencing. TTAs/CTAs associated to incoming flights will be taken into account at airports for Runway Management and Surface routing and guidance.

Multiple Target/Controlled Times can be issued along the trajectory to ensure synchronization/separation of traffic not only in approach and landing phases, but also during all phases of flight. Such soft and hard time-constraints are respectively called Target Time Over (TTO) and Controlled Time Over (CTO) and will represent a –negotiated– trade-off between the airspace users preferences and the network capacity available. Note that between two consecutive 4D restrictions (whatever TTOT, TTO/CTO or CTO/CTA) the Airspace User will be able to plan and execute its trajectory with some navigational looseness, which will leave room to the navigational systems to find the most optimal procedures to meet with the targets/constraints while considering the presence of small flight uncertainties such as wind/weather forecast imprecisions, and potential tactical (self-)separation events that will be only known with precision at the moment (or few minutes before) of operations.

Tactical monitoring and separation provision will still be a responsibility of ATCOs, thus they will be properly trained and equipped to adapt to their tasks to the new ATM concept procedures, especially with the potential introduction of more advanced and automated DSTs that may be able of coordinating with the rest of the stakeholders DSTs through a common ATM state-space overall view (i.e., the NOP) [71], thus aiding to assess the network impact of their local decisions while reducing the task-load of controllers associated to repetitive and monotonous tasks.

1.5.6 Summary of the SESAR ATM Concept

SESAR aims at completely modernizing the CNS technologies and ATM procedures in order to achieve the following main (high-level) goals: to increase the air traffic system **capacity**, the flight **efficiency** and the **safety** in order to allocate future expected airspace demand while reducing **ATM direct costs and environmental impact** per flight.

The most important differences with respect the current ATM concept are identified as follow:

- **Trajectory Based Operations (TBOs):** which implies the usage of 4D trajectories (trajectories defined in the 3 spatial dimensions together with a time-stamp), also known as Business Trajectories (BT) in the SESAR's terminology for civil flights. The BT evolves out of a collaborative layered planning process, through which it progresses from the form of a Shared Business Trajectory (SBT), which is shared for planning and negotiation purposes with all the involved stakeholders, to the Reference Business Trajectory (RBT), which is instantiated few minutes before the flight execution, and represents the trajectory which the Airspace User agrees to fly and the Network Manager, the Air Navigation Service Providers (ANSPs) and the Airports agree to facilitate [102, 5].
- **Improvement of the infrastructures of Communication, Navigation and Surveillance systems (CNS), Meteorological services**

(MET) and ground/airborne Trajectory Predictor systems (TP): the progressive improvements of ATM technologies will lead to improved performance of both flight planning and navigation execution. The enhanced coordination of the airborne systems with the controllers' support tools together with the availability of high quality trajectory predictions (greater accuracy and longer prediction horizons), will be a fundamental enabler for TBOs, which in turn will imply a reduced controller workload per flight (fewer clearances with longer effective duration).

- **NOP through SWIM and CDM:** SBT negotiations and RBT acceptances are managed and published through the NOP (Network Operations Plans), which is accessed and contributed by the Airspace Users, the ANSPs, the Airports and the Network Manager over the SWIM platform. The introduction of modern technologies (e.g., data-link, P-RNAV, ADS-B…) combined with the development of specific ATM procedures based on TBOs (e.g., online RBT re-planning) is intended to provide the traffic managers with more flexibility to dynamically reconfigure the airspace to adapt it to the ATM changing conditions (e.g., severe weather affecting sectors/airports capacity, system disruptions, Flexible Use of Airspace...) and to the user-preferred routing [110, 73].

- **User preferred/Free route operations:** this will imply the relaxation of the structured routing constraints for flights, supported by new CNS technologies (CPDLC, P-RNAV, ADS-B…), and implying the possibility for the Airspace Users to plan their trajectories freely between a defined entry point and a defined exit point of the free route airspace, with the possibility of deviating via intermediate navigation points without reference to the fixed route structure, which implies important fuel savings and pollution reduction with respect the current fixed route procedures [103, 105]. During high-complexity operations at certain airspace regions the Free-Routing might be suspended by NM or ANSPs that can issue 2D, 3D or 4D airspace constraints to separate and/or synchronize traffic.

- **Automation support tools for ATCOs and new separation and synchronization modes:** Within free route airspace, flights will remain at all times subject to air traffic control and to any overriding airspace restrictions. However, the new advanced CNS groundside and airborne capabilities will enable the introduction of new separation modes such as the aircraft self-separation and the strategic de-confliction of the flight routes/trajectories, which together with the automation support to the new and traditional ATC tasks (situation monitoring, medium term conflict detection, conflict resolution, etc.), will be one of the principal changes for increasing airspace capacity.

Moving **from current short-term tactical instructions to more strategic 2D, 3D and 4D clearances**, i.e. Strategic De-confliction, and providing **with the proper automation support** (though different advanced and coordinated DSTs) to aid and reduce a portion of the ATCOs workload is the main strategy followed by the SESAR concept in order to achieve the targets of increasing capacity and safety in the ATM while reducing costs. The air-ground harmonization of the trajectory predictions, supported by robust meteorologic forecast (wind, temperature, etc) and shared via data link, improves significantly the accuracy and reliability of trajectory data used for decision making, especially for ground-based tools, thus enabling longer usable prediction horizons and permitting the issue of longer duration clearances.

The main strategy followed to improve flight efficiency and to reduce costs and pollution is to **allow the direct involvement of AUs into the ATM planning process**, by means of a **Collaborative Flight Planning** based upon a dynamic rolling Network Operations Plan (NOP) that provides a common reference view of the ATM state-space that is available to all stakeholders through SWIM communication network. Therefore, airlines are able to optimize their business trajectories while ANSPs can update the actual available airspace/ATM capacity in real-time [39, 40].

The Network Manager (NM) will be in charge of coordinating and arbitrating those DSTs processes in which the local decisions might negatively affect the rest of the ATM network operations, especially along those decision-making processes in which the *flight safety* could be compromised (e.g., during Collaborative Flight Planning), thus taking action by means of prioritization or imposition of final decisions to ensure the proper levels of safety during the execution of all flight phases. The NM generates, if necessary, a set of time constraints assuring that the local airspace sector capacities are not overloaded at any given time.

Thus, at the end of the trajectory synchronization process (through a transparent, accessible and fair Collaborative Flight Planning process arbitrated by the NM), a cost-efficient network of pre-deconflicted 3D (free-)routes is expected (subject to dynamic refinement or adjustment during flight, i.e. 4D contracts), which constitutes a paradigm shift with respect to the current airspace structure (often based on predefined fixed airways) and ATM procedures.

Figure 1.9 illustrates a simplified block diagram showing the SESAR ATM planning concept. Note that this ATM model will reduce the existing gap between the CFMU flow management (current NM) and the ATC tactical traffic management processes through joining the strategic conflict management (i.e., network and flight planning phases, which can now be dynamically changed according to

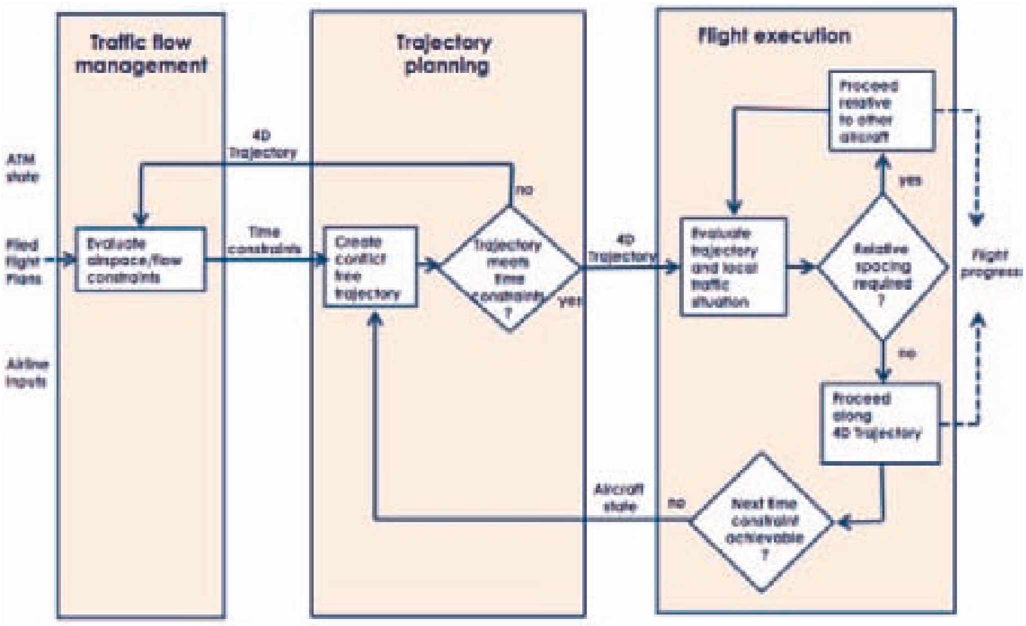


Figure 1.9: Simplified representation of the future ATM system

The future SESAR ATM concept will allow the participation of the airspace users during the re-allocation of airspace resouces and re-plannig of the 4D trajectories. The aim is to reduce the latent ATM capacities at the maximum extent and to use all the resources with the maximum efficiency possible. Safety will be ensured through various layers of traffic planning and conflict management.

the feedback received from the ATM updated state) with the tactical conflict management conducted during the flight execution. The system is trajectory-based, so a micro-scale model of the traffic flows is needed. There is also a time-based traffic flow/trajectory management (i.e., adjustment of the trajectories at the planning phase articulated through Target/Controlled Times) with the purpose of achieving strategic separation and traffic synchronization along the network. The tactical safety layer is in charge of assuring local spacing in the flight execution phase, although due to the strategic de-confliction measures and the airborne self-separation mechanisms it is expected to trigger trajectory re-planning feedback requests only in exceptional cases. The NM, that is monitoring the available (dynamically) declared airspace/ATM capacities, generates if necessary a set of time constraints assuring that local airspace sector capacities are not overloaded at any time. During the planning phase of flights, also monitored by the NM, a set of conflict free trajectories is generated that comply with all these network constraints (i.e., strategically de-conflicted flight routes/trajectories).

If a trajectory that meets the requirements cannot be generated during the trajectory-planning negotiation (e.g., due to aircraft performance limitations), a new alternate preferred trajectory will be generated and fed back to the NOP in order to find a new set of time constraints that can be actually accommodated. Once a feasible 4D trajectory has been generated, the flight will be executed along such 4D trajectory unless there is a local spacing separation requirement with another aircraft (e.g., due to the de-synchronization effects of uncertainty) or if there is a change in the network restrictions (e.g., a sector capacity reduction due to the uncertain conditions of weather). In the first case, i.e., a local loss of separation, the local situation can be resolved relative to the other aircraft and, in case that any of the amendments results in a relevant deviation from the reference 4D trajectory, a new (strategically de-conflicted) 4D trajectory will be cooperatively planned. In the second case, i.e., relevant changes at network level, it is expected that a higher number of trajectories will be re-negotiated (and strategically de-conflicted) in response to the new ATM conditions and with the goal to efficiently balance the available capacity and demand.

ATCOs working method will be updated in the SESAR context since controllers will have to comply with specific 4D constraints to guarantee that the flights meet their agreed RBT. This shall not necessarily increase their workload, since they will be provided with clear targets to be met by flights, automated DSTs suggesting priorities and maneuvers for resolving conflicts and increasing situational awareness and whenever possible some separation functions will be delegated to aircraft onboard systems (i.e., self-separation). When required, the necessary trajectory revisions/updates will be made in due consideration of the *complete trajectory* still to be flown and not only at sector level (thus opening the possibility to take into account the wider impact on other flights' concerned trajectories as well as on the network operations, i.e. domino effects/emergent dynamics of the local decision-making).

1.6 The Motivation of this Research: the STREAM Project

STREAM (Strategic Trajectory de-confliction to Enable seamless Aircraft conflict Management) [http://www.hala-sesar.net/stream] has been a SESAR funded WP-E project (i.e., long term innovative research to contribute to the SESAR ATM concept) that has been undertaken by a consortium integrated by Advanced Logistics Group (ALG-Indra), Boeing Research & Technology Europe (BR&TE) and Universitat Autònoma de Barcelona (UAB).

The main goal of this project (which is also the goal of this dissertation) has been investigating **innovative computational-efficient Conflict Detection and Resolution (CD&R) algorithms for strategic de-confliction of thousands of trajectories** within few seconds or minutes taking into consideration the AUs preferences and the network constraints. This is aimed at enabling traffic to be de-conflicted for **wide airspace regions** and permitting **large look-ahead times** of order of hours (e.g., two or three hours), which can reduce the current existing gap between the conflict management processes conducted during the pre-departure planning and the flight execution phases [36, 88, 37, 43, 48].

Therefore, the underlying concept is **extending the NOP continuously-rolling planning concept to separation management** by means of a seamless conflict management process that would run continuously from the strategic phase (pre-departure, collaborative design of the NOP) up to the execution one (automation-assisted, controller-driven conflict resolution). **This doctoral dissertation will give results and details and will discuss about the functionality, limitations and benefits of the proposed CD&R module [43, 48].**

In addition, during the project **new metrics and a performance assessment methodologic framework have been proposed** [44] to evaluate the performance of such CD&R algorithms as well as the potential impact of the solutions on airspace users and on the ATM system. For instance, a metric to measure the fairness of a trajectory de-confliction solution has been defined, in order to evaluate how fairly the cost penalties associated to the deviations from the original SBTs proposed by the de-confliction algorithms are distributed among

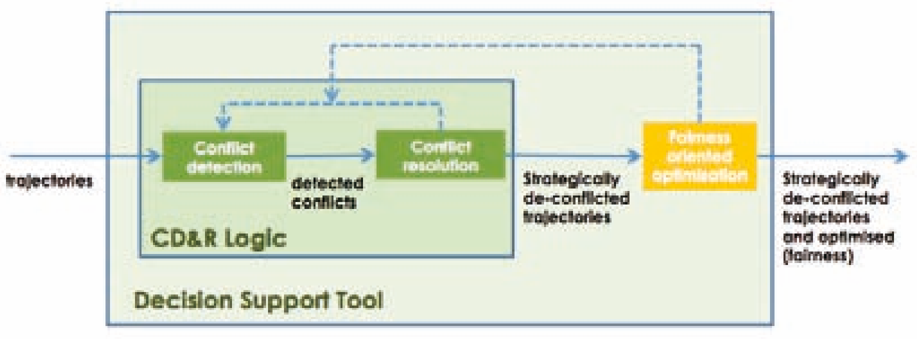


Figure 1.10: STREAM proposed Decision Support Tool for strategic conflict management and traffic planning

The STREAM project has proposed a Decision Support Tool consisting on a Strategic Conflcit Detection and Resolution system that provides the Network Manager with several conflict-free traffic scenarios, and an additional module that applies several metrics (such as fairness) to select the most prefered scenario according to the weighed preferrences of all the stakeholders.

the airspace users. See Fig. 1.10. However, **the main work presented in this doctoral dissertation concerns only to the CD&R module and hence the definition and utilization of these particular metrics will not be discussed.**

1.7 Objectives and Dissertation Structure

This doctoral dissertation (which is fundamentally linked to the SESAR WP-E STREAM project) proposes the design and implementation of innovative **strategic trajectory de-confliction algorithms** to be applied prior and/or during flight execution of a **large number of 4D trajectories at wide regions of airspace** (e.g., the European airspace), based on the enriched and distributed information potentially available before the aircraft take-off and updated during the execution phase through a continuous rolling flight planning negotiation process.

For that purposes it is necessary to develop an **ATM micro-scale model framework that must be able to store and manage the precise description of all the 4D trajectories in the ATM system under consideration**, thus enabling **a centralized and complete view of the current state-space of the system and its evolution along the time**, which is necessary to **observe the potential emergent dynamics** when a local decision is made. This technological contribution could help the NM, in an automated way, to:

- Maintain or improve the levels of **safety** within the en-route sectors at European airspace scale by applying early de-confliction measures and considering some levels of uncertainty.
- Improve the European ATM **capacity** by delivering the en-route traffic already (fully or partially) de-conflicted to the tactical conflict management phase conducted by ATCOs, thus reducing the numbers of necessary tactical ATC interventions (specially at more congested sectors during peak hour of traffic).
- Provide with **efficient** and **environmental-friendly** trajectories, by means of minimizing the trajectory changes with respect the user-preferred RBTs (simplified here as Direct Routes), always considering the full trajectory (simplified here from TOC to TOD, in an airspace in which the semi-circular cruising level system applies), and also through the minimization of the potential negative network emergent dynamics/domino effects derived from the local decisions (while taking advantage of the potential positive domino effects whenever possible).
- Be consistent with the future procedures and tools of **SESAR** (e.g., 4D navigation, Free-Route, Strategic De-Confliction, Dynamic Route Allocation, Collaborative Flight Planning. . .)

The **implementation** of the system has been done in C++ with an Object Oriented approach, and several **simulations using realistic scenarios** have been performed and analysed to verify the correct functioning of the concepts.

The dissertation is divided in 7 chapters. First Chapter is the **Introduction**, which corresponds to this chapter, and that will be used as a baseline for the rest of the chapters.

Second Chapter is about the **State of the Art of Conflict Detection and Resolution** algorithms, in which the extensive bibliographic review conducted during the research is summarized in order to let the reader the easy understanding and identification of the most important concepts presented along this dissertation.

In the third Chapter a summarized high-level description of the **Conflict Detection and Resolution Algorithms for Strategic De-confliction** can be found, giving details about the main assumptions of the approach as well as the technologies used in the CD&R algorithms.

In Chapter 4 a **Guidance and Chronology of the Published Articles** is included, which explains the chronological and logical sequence of the articles presented in this dissertation (in Chapter 7) in order to guide the reader in the understanding of the thematic unit of the papers and in the gradual presentation of the results.

Chapter 5 presents the **Scenario Design, Simulations and Discussion of Results** in which the concepts and findings introduced in the previous chapters are critically argued related to their potential contributions to the SESAR ATM 2020 and beyond paradigm.

Chapter 6 will read the **Conclusions, Main Contributions and Future Work** in which the conclusions and main contributions extracted after the analysis of the results will be stated while a set of research lines will be proposed to extent some of the identified topics.

Chapter 7 includes a **Compendium of Published Articles** in first-order international journals and/or relevant congresses. Those papers constitute the core of this dissertation and thus the most relevant details and findings of the research can be found in that chapter.

Finally, the **Appendixes** include some other sections that give more detailed information about some important aspects of this research, but that do not conform part of the core and main line of argument of this dissertation.

Chapter 2

State of the Art

2.1 System Classification by the Look Ahead Time

Conflict Detection and Resolution Systems can be classified according to their working prediction time-horizon (i.e., look-ahead time) [75, 47]. Hence, three different categories can be found, each of them furnishing different functionalities since they respond to different airspace management needs:

- Long Term CD&R (LTCD&R): useful for airspace planning at strategic level (a.k.a. Strategic De-confliction). It includes the planning of all air traffic trajectories within a look-ahead time-window of several hours (e.g., 2 hours). Predictions are made from several days up to few minutes before the flights execution phase. The main goal of these systems is to maximize the network route efficiency while minimizing the global operational costs, taking into consideration the airspace/network restrictions such as the available capacity at the airports and sectors, among other restrictions [47, 14, 83, 11, 88].

- Medium Term CD&R (MTCD&R): planning systems that work at tactical level, thus considering prediction look-ahead time-horizons of several minutes (typically 20 minutes). These systems are often used by air traffic controllers due to the presence of disturbances caused by unforeseen events that cannot be predicted beforehand with enough accuracy (i.e., during the strategic flight planning) and that usually make impossible to accomplish with the LTCD&R's proposed flight plans during the execution phase. Note that the MTCD&R systems are planning tools rather than collision avoidance systems, since the time-window look-ahead time is large enough to allow a safe tactical planning and thus there is no risk of any imminent crash among airplanes [52, 107, 28, 111]. Therefore, it is possible to use these systems to optimize the trajectoriy amendments when tactical ATC traffic changes are required, while trying to maintain stable at the maximum extent possible the strategic network planning proposed by the LTCD&R system.

- Short Term CD&R (STCD&R): systems that work at operational level and whose main functionality is to avoid imminent crashes. Since they are not planning systems, no fuel or flight optimization is taken into consideration. These systems include alert mechanisms for controllers, e.g. Short Term Conflict Alert (STCA), as well as alert mechanisms for pilots, such as Traffic Alert and Collision Avoidance (TCAS), both based on Automatic Dependent Surveillance-Broadcast (ADS-B) technologies [62, 33, 29]. Note that ideally the triggering of these systems should be avoided by the strategic and tactical traffic planning layers, i.e., the Strategic De-confliction and MTCD&R systems.

2.2 Current Situation of CD&R Systems in ATM

Currently, air traffic controllers' tasks are **supported by systems with little levels of automation in the decision-making functions** [87, 101], thus requiring of comprehensive human intervention in a large set of repetitive operations that do not always generate added value to the navigation services provided by the ATM, such as for example the traditional requests to pilots to tune the radio frequency of the next sector (modern avionics can automatically tune itself without increasing the workload neither of the controllers nor of the pilots). In addition, some of the airspace safety prescriptions given by the International Civil Aviation Organization (ICAO) [58] may often result in relatively conservative and inefficient procedures, both from the point of view of the fuel consumption and of the airspace sectors capacity utilization. For instance, due to traffic de-synchronizations observed in the current ATM, air traffic controllers frequently demand to pilots to execute holding procedures in order to have the airplanes in safety airspace zones, flying in circular patterns while awaiting for further clearance. Such procedures are especially frequent during approach and landing operations in which the holding aircraft must wait to other flight landings or take-offs (see Fig. 2.1).

The official European Commission predictions about the future demand of the air transportation (which expects important lack of airspace capacity for the year 2030), have fostered in recent years the interest for finding new positioning and navigation technologies, as well as new traffic-awareness technologies, and also new improved ways for communications between the airside and the groundside (currently most communications between pilot and controller are still done via voice). New Decision Support Tools have been also developed to aid controllers in some of their tasks, altogether with the purpose to improve the capacity and the efficiency of the ATM. Conflict Detection and Resolution systems are examples of

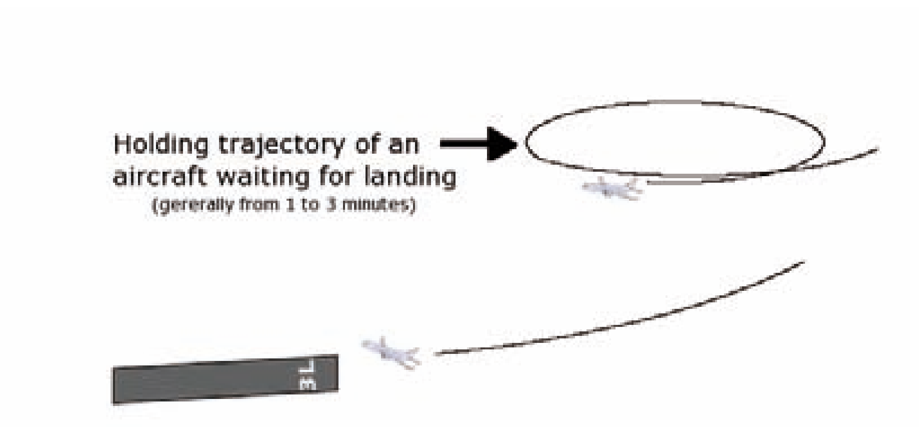


Figure 2.1: Holding procedures

Holding procedures consist on flying in circular patterns while awaiting for further clearance. These procedures are often consequence of the traffic de-synchronization effects and thus they are considered inneficient in terms of flight efficiency since important costs can be saved by improving the ATM predictability and the traffic syncrhonization.

these automated tools that can contribute to give support to air traffic controllers, particularly in their tasks of traffic separation.

There are different ways to classify the Conflict Detection and Resolution algorithms based upon several characteristics identified in a study conducted by Kuchar & Yank in which 68 different CD&R models were analysed [65, 64]. According to such comprehensive survey, **there are three different methods to model the aircraft state propagation**: first, making a *nominal* prediction of the future aircraft/trajectories states (i.e., with no uncertainties associated to flight execution), second, taking into account the *worst-case* scenario (i.e., the most extreme manoeuvre feasible during flight execution, thus considering potential changes –i.e., uncertainty- in the executed trajectory with respect the planned one), or third, considering a *probabilistic* state propagation model in which the nominal trajectory is modelled with the highest probability values and the most extreme manoeuvres are also considered as feasible but associated with lower probabilities of occurrence. (See Fig. 2.2)

Other key aspects for the algorithms classification are the **number of state variables**. Some of the algorithms work in two dimensions, usually in the *horizontal plane* (i.e., heading and/or speed changes), although there also are some algorithms that exclusively work in the *vertical plane* (i.e., flight level changes). Other algorithms can also work detecting and solving conflicts in *3D spaces*.

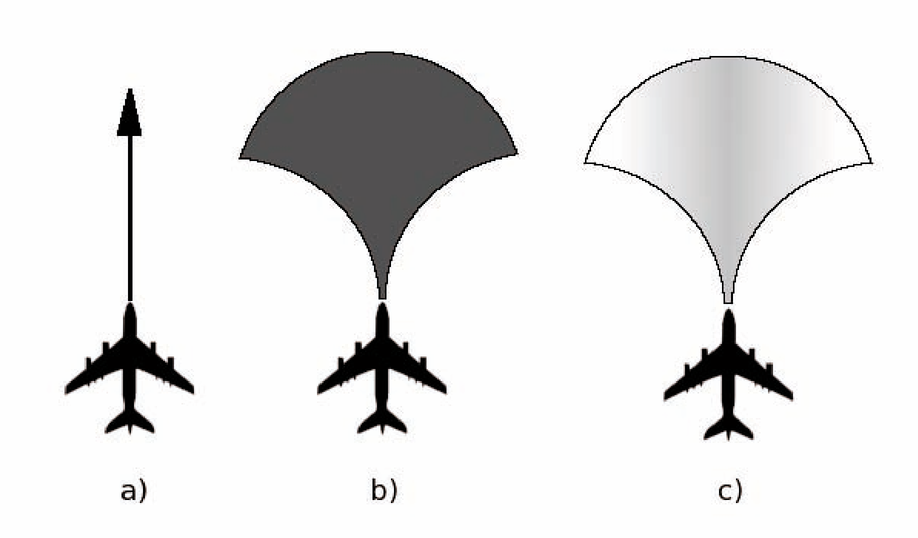


Figure 2.2: Models of aircraft state propagation during flight execution

In general, three different models of state propagation are considered: a) the nominal model that considers full certainty model about the future positions of the aircraft, b) the worst-case model that considers the most extreme maneuver that the aircraft could execute, and c) the probabilistic model that assigns different probability values to each feasible state.

Another feature of the CD&R systems is the **resolution method**. Generally, the different types of resolutions might be classified as *prescribed resolutions* (a.k.a. “rules of the road”), *heuristic optimization models* (for example, genetic algorithms, expert systems or games theory), *analytical equations* (e.g., Force Field methods) or *manual resolutions* based on human intuition (therefore with automated support only for conflict detection).

The **type of manoeuvres** that are used to propose the trajectory amendments is also an important characteristic to distinguish among the different algorithms. Basic de-confliction manoeuvres are *heading angle changes*, *flight level-altitude variations*, or *speed changes.* A *mix* of any of these three basic types of manoeuvres might be also an option to solve conflicts.

Another relevant characteristic among the different CD&R algorithms is how they process detection/resolution when **multiple conflicts** arise among two or more trajectories. If the algorithms sequentially detect and solve the conflict through the consideration of the minimum safety distances between each pair of trajectories without concerning of the rest of the trajectories in the network, then they are based on a *pairwise strategy.* In contrast, if the entire traffic situation is examined simultaneously, they are based on a *global strategy.*

Other model elements are also important, for instance how the algorithms manage *uncertainties*, or whether the algorithms consider *cooperative resolutions* or not.

Finally, it is also convenient to determine whether an algorithm *can be actually implemented* with the current available technology and, in such a case, if the algorithm is able to *operate in real time* basis.

Kuchar & Yang’s survey concludes that none of the analysed algorithms might be considered strictly better than the others, as all of them present relative advantages and disadvantages, and thus all might be useful in different circumstances and/or for different purposes.

Many of the investigation efforts done in the CD&R field have been also focused on the designing and implementation of systems for real operational ATC purposes. As a result, some of the first automated decision support tools for air traffic controllers have emerged from the 80’s up to recent times (SCTA, CTAS, VERA, ERATO, VAFORIT, URET, FASTI, CORA, or iFACTS, among others) [86, 33, 24, 60, 2, 55, 94, 10].

According to the research done by Ehrmanntraut, Fricke and von Villiez [86], the CD&R systems have been historically oriented to aid decisions at local airspace-sector level, with a look-ahead time typically limited to a maximum of 20 minutes (i.e., tactical applications) and lacking of a global perspective on how the decisions made at the local level may affect the rest of the network. Only the academic approach (i.e., non-operational) developed by Dr. Durand (and whose approach makes use of Genetic Algorithms applied to strategic en-route conflict resolution) has been focused on computing conflict-free trajectory scenarios with a global optimization scope while obtaining the solutions in timely manner [16, 53].

On the other hand, the Programme for Harmonised ATM Research in EUROCONTROL (PHARE) developed during the 90's (1989 to 1999) [21, 86], was the first conflict solving assistance concept that used the concepts of *4D trajectory management* from gate to gate through multi-sector planning. However the proposed CD&R system only included automated conflict detection (conflict probe) but not automated conflict resolution. Instead of this, a set of co-operative tools together with the Problem Solver was investigated in order to provide assistance to the controllers for de-conflicting the trajectories with some coordination with other downstream sectors.

More recently, the project ERASMUS [50] aims at strategically de-conflict part of the traffic by adjusting the 4D Business Trajectories through minor speed adjustments (subliminal action) not directly perceivable by controllers and that will not interfere with their own action and responsibility. ERASMUS estimates that the residual number of conflicts to be considered by controllers could therefore be significantly lowered, thus reducing the controller's workload associated with routine monitoring and conflict detection as well as reducing the interventions of ATC in changing flight profiles to resolve potential conflicts. Nevertheless, the results of the project showed that subliminal control speed can only slightly contribute to the strategic de-confliction of traffic, and therefore other complementary strategies should be applied.

Hence, based on the current state of art of the CD&R systems, it can be stated that there are still many research lines opened for further study in the field of CD and CR algorithms, and in particular in the area of strategic de-confliction according to the SESAR's objectives established to enable the future European ATM.

2.3 Strategic De-confliction

Today, traffic is strategically organized to avoid/minimize conflicts. Such ordering is achieved via approach and departure routes, jet routes, the hemispherical altitude rule, step climbs, and so on. Free Route operations will imply the relaxation of structured routing constraints for flights, further implying the possibility for the Airspace Users to plan their trajectories freely between a defined entry point and a defined exit point of the free route airspace with the possibility of deviating via intermediate navigation points without reference to the fixed route structure. Within the free route airspace, flights must remain subject to air traffic control at all times and to any overriding airspace restrictions [41, 105, 103].

The introduction of modern communication, navigation and surveillance technologies combined with the development of specific ATM procedures is intended to provide traffic managers with a greater degree of flexibility in dynamically reconfiguring airspace to adapt to changing conditions (e.g., convective weather disruptions, Flexible Use of Airspace or any other unforeseen event) and to user-preferred routing [110, 73, 47] .

The development and implementation of a CD&R system for **Strategic De-confliction could enable Free Route operations** applied along the entire European airspace, **therefore allowing the Airspace Users to plan their optimal/prefered flight trajectories**. After a certain level of strategic conflict management and traffic synchronization, the final RBT assigned to each flight may include pre-de-conflicted 3D routes subject to dynamic refinement or adjustment during flight. This situation constitutes a paradigm shift with respect to the current airspace structure, which consists of a set of predefined airways that depend on a ground-based infrastructure of navigation aids and rely on the subdivision of the airspace into ATC sectors aimed at facilitating the management of flights.

Currently, **the traffic planned at strategic level** (i.e., from several hours in advance up to 20 minutes) **is subject to a lot of uncertain**ty, and thus it becomes a major issue that notably affects the CD&R algorithms that are designed for strategic de-confliction purposes [65, 64]. Recently, five categories of uncertainty that affect the ATM are under discussion by the scientific community [1], i.e., Airborne Trajectory uncertainty (i.e., uncertain prediction and execution of the planned trajectories), Flight uncertainty (e.g., departure delays), Traffic uncertainty (i.e., uncertainties affecting flows and airspace sectors), Network uncertainty (i.e., strong disturbances, such as adverse weather) and Weather uncertainty (i.e., the weather is interpreted as a system that behaves independent of, but affects to, the ATM system).

The availability of consistent representation of predicted Business Trajectory is paramount to achieve interoperability and consistency between the ATM Decision Support Tools (DSTs) [71, 20]. However, trajectory prediction is inexact, first due to the wind forecast inaccuracies and second due to tracking, navigation and control errors [17, 75]. In [16, 53], the speed uncertainties due to wind prediction errors are identified as the most important factor affecting the en-route trajectory predictions and thus the robustness of the CD&R solutions. However, with the introduction of the 4D-Flight Management Systems (4D-FMSs, which are currently being fostered by the SESAR programme), **the control and guidance of an aircraft are becoming increasingly accurate, thus reducing these uncertainties that affect the airborne flights**.

Therefore, taking into account the current technological progresses in connection with aircraft' positioning and navigation, it seems possible to think in a CD&R system that manages a **nominal state propagation** of the airborne aircraft trajectories. This implies the assumption that the planned trajectories will be flown by the aircraft with enough precision at all the times during the flight execution phase (trajectory deviations will be always present, but they will be relatively small thanks to the advanced 4D navigation systems, so they can be tackled with extra safety distance between aircraft, i.e., a safety buffer added to the nominal safety distance [56]).

On the other hand, if a Free Route airspace is considered, then it seems logical that a strategic CD&R system should be able of detecting and solving the conflicts in a **3D environment** (even if the hemispherical altitude rule applies) while allowing **all types of resolution manoeuvres** such as heading changes, altitude changes and speed variations. In this manner, the system can achieve more realism and flexibility during the search of conflict-free scenarios while still leaving room to potentially obtain more efficient resolution trajectories.

Other important sources of uncertainty affecting the flights, and thus the traffic synchronization, are the *delays*. Nevertheless, according to [38] most of the primary delay causes are associated to ATFCM decision-making, which in turn is affected by the current ATM concept (prefixed routes, ATC sectors, and so on). Therefore the development of a strategic CD&R system that works with gate-to-gate 4D trajectories could contribute to mitigate some of the primary delay sources as well as the reactionary ones. Hence, it is interesting that the developed **CD&R algorithms can consider the state space of the full air traffic system from an overall network perspective**, thus being able to **assign conflict-free 4D trajectories to flights with a global strategy over all the trajectories and conflicts present in the scenario** rather than using a pairwise approach that is not efficient at finding global-optimal solutions. Other strategies to deal with the remaining delays should be also considered (e.g., the temporal looseness, discussed in the Appendix A.5).

Note that with a global perspective it is also **possible to observe the potential emerging dynamics derived from the decisions made at local level**, e.g. a resolution trajectory generated for solving a conflict between two trajectories could generate new interactions (i.e., *downstream conflicts*) that previously did not exist in the network. Also it might happen that a resolution manoeuvre could solve not only the original conflict but also other potential upstream or downstream conflicts that were previously present and involved the original trajectory. These emerging interactions that appear in the network (or the elimination of pre-existing interactions) are known as *"domino effects"* or more formally as *network effects* [69]. When a trial resolution trajectory generates new network interactions, this is referred to as a *destabilizing effect* (i.e., negative), whereas a *stabilizing effect* (i.e., positive) occurs when one local conflict resolution indirectly solves one or more downstream conflicts. In [61, 66], the authors underline the **importance of taking into consideration these domino effects** in the design of a CR system because these phenomena notably affect the quality of the resolutions from the network point of view and are thus a necessary condition for the adoption of an effective global strategy in the CD&R system for providing optimal conflict-free network solutions.

Finally, according to [110], **convective weather** is currently identified as one of the ATM uncertainty factors that most seriously affect the network route structure, **thus requiring real-time algorithms to reconfigure the airspace**. In [16], Durand argued that the complexity of conflict resolution with global optimization for n aircraft is a Non-deterministic Polynomial (NP) combinatorial problem with $2^{\frac{n\cdot(n-1)}{2}}$ possible solutions. Due to such a huge solution space, no efficient analytical mathematical solution is known for finding optimal global solutions.

A simplified 4D nominal traffic model is assumed in the scenarios of this dissertation (i.e., no weather perturbations, no contingency events nor other sources of uncertainties are considered in the traffic model), but in order to deal with real useful applications (i.e., strategic network de-confliction with a large number of trajectories and uncertainties in the ATM system), the strategic CD&R system design has been focused on the **computational efficiency** as it must be able **to execute in a reasonable time in order to dynamically reconfiguring airspace** to adapt to potential changing conditions (e.g., convective weather disruptions, Flexible Use of Airspace or any other unforeseen event) and to user-preferred routing [110, 73]. Refer to Section 3.3 and Appendix A.5 about Uncertainty to see how **many different sources of uncertainty could be**

supported by the CD&R model design presented in this dissertation.

Chapter 3

Conflict Detection and Resolution Algorithms for Strategic De-confliction

3.1 Data Framework to Store and Manage the ATM State-Space Information

The Spatial Data Structure (SDS) is a database that represents a spatial region (e.g., an air sector) by using individual memory positions to represent each of the discrete (3D) coordinates of the sector [98, 97, 96]. Such memory positions are sorted in a way that, given a certain coordinate, the spatial information stored inside the SDS (associated with such a coordinate) is easily recoverable by applying linear functions (for more information see the Published Articles 1 and 2 on pages 131 and 155 respectively). The SDS can be conceptually represented as a mesh of discrete points distributed throughout the space region that is considered in the scenario, as shown in Fig. 3.1. Note that inside this three-dimensional SDS, i.e. the cube of the figure, a discretized 4D trajectory (different 3D positions of an aircraft in different discrete time steps) can be found.

SDSs facilitate the storage and efficient processing of *spatial data*, which might be composed of *spatial information* (e.g., a discrete representation of either the flight trajectory or its corresponding enveloping safety tube) and *non-spatial information* (e.g., the time-stamps of every discrete trajectory or tube samples, together with the flight identification number). A common way to deal with the non-spatial component of the spatial data is to store it explicitly in one or several fields in the same database record associated with the spatial information component (i.e., the occupied coordinate) of the desired item (e.g., a flight trajectory discrete sample) [98, 97, 96].

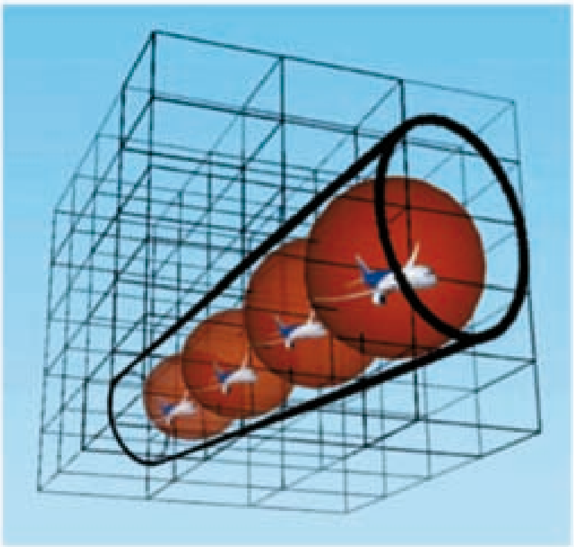


Figure 3.1: Conceptual representation of the psysical shape of a Spatial Data Structure (SDS)

A certain airspace can be modeled through Spatial Data Structures, which link the spatial information geo-refered to a certain coordinate with the particular records and memory positions of a computer database. These database records are sorted/structured in a way that the spatial information inside can be efficiently read and/or written through mathematical linear functions that receive the airspace coordinate values (i.e., lat, long, altitude) as input.

SDSs have been explored under the STREAM project as a data framework to implement pairwise-comparison filtering techniques in the CD process, with excellent results in terms of time performance due to the linear computational complexity [68, 95], O(n), of the CD algorithms based on SDS [13, 12, 6, 93, 89](see Articles 1 and 2 on Chapter 7). The SDS capability to efficiently store spatial data (e.g., 4D trajectory information) at the time when the conflict detection among all SBTs/RBTs is performed, together with the efficient database access methods, have been a key factor for the development of new tools to store and analyse the entire ATM State-Space (SS) information under a global scope in which the entire traffic situation (i.e., all the 4D trajectories in a 2-3 hour time window) is examined simultaneously. A simplified 4D dynamic model is assumed in this dissertation, i.e. aircraft position and velocity at each time-step, so uncertainty and stochastic events are not considered in the traffic model.

This data framework can enable a complete and precise identification of the emergent dynamics that new trajectories may cause in the network, i.e. "domino effects" (see Article 3 on page 183 and Article 5 on page 205). Causal models can be employed to provide with a strategically de-conflicted flight route allocation conducted with a global scope, based on the SS information stored in the SDS since all the processed trajectories (original and alternate) will remain stored as a "4D snapshot" of the ATM system (see Articles 3 and 4).

The concept of SDS is further explained in the Articles 1 and 2 included in the Compendium on page 129 of this dissertation.

3.2 Concept of Operations

The STREAM conflict detection and resolution tool has been **designed to be compatible with the SESAR tools and procedures**, but represents an evolution towards a seamless realization of conflict management (from strategic to tactical), starting before the flights takes off (SBT modifications) and continuing through the complete flights duration (RBT modifications). The necessary input data for executing CD&R system (in this simplified case, the 4D trajectories) will in general be available to the system through the NOP (see Appendix A.1 about SWIM integration). See Fig. 3.2.

Relying on the SBT/RBT and Strategic De-confliction SESAR concepts as well as on the assumption of the general availability of a 4D-FMS navigation system, the STREAM solution adopts a combination of different resolution strategies (route, speed and flight-level modifications) that will be applied to **de-conflict**

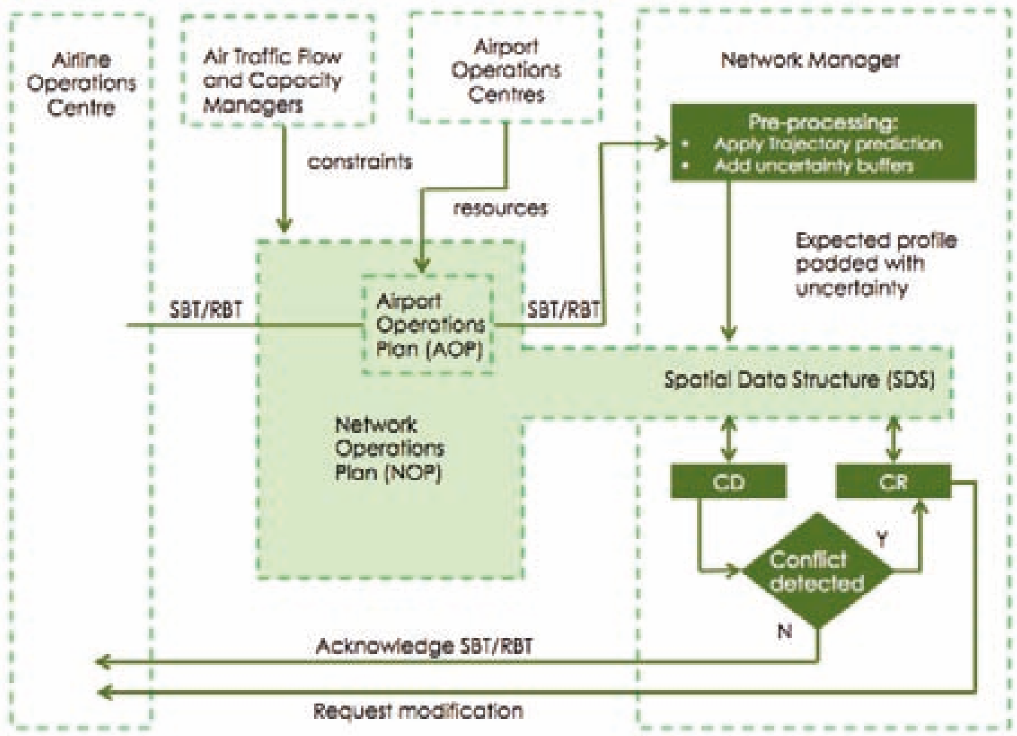


Figure 3.2: STREAM air traffic planning concept based on the SESAR ATM concept of oferations

The ATM plannning architecture proposed by the STREAM project is based on, and is compatible with, the SESAR ATM concept. The Strategic CD&R tool is supposed to be under the control of the Network Manager and is based on the use of Spatial Data Structures that will be fed with the available information though the NOP/SWIM, in which the main ATM stakeholders can share their intentions and negotiate the use of the airspace resources.

the involved SBTs and RBTs at a strategic level by taking into account the characterization of the conflict (i.e., type, location and duration) and the preferences of the Airspace Users [43, 48, 88].

The idea is to capitalize on the availability of the 4D trajectory information available prior to take-off (i.e., SBT) or from the actual flight (i.e., RBT) with the highest accuracy possible depending on the planning horizon. The analysis of this information will allow the Network Manager, in close cooperation with the Local Traffic Managers (i.e., ATCOs) and the Airspace Users, to build an "uncertainty 4D tube" by adding buffers around each nominally predicted trajectory in order to **create a picture of the traffic evolution that could contribute to increase the robustness to certain sources of uncertainty** (e.g., navigation and tracking errors, tactical delays, risk of trajectory deviation, etc.). Unexpected events such as trajectory deviations that require tactical interventions (i.e., aircraft flying outside the 4D tube) could still occur, and thus the ATC Officer clearances will continue to be necessary. However, the overall predictability of the system will be enhanced, thus implying fewer tactical interventions and more stable plans.

The outputs of the STREAM CD&CR algorithms are the proposed amendments to SBTs/RBTs that are anticipated during the flight planning in order to avoid/minimize conflicts during the execution phase. A precise Trajectory Prediction enables the algorithms to detect the potential conflicts and to guarantee that the proposed SBT amendments will result in conflict-free trajectories. Consequently, **the effectiveness of the algorithms is strongly dependent on the accuracy and robustness of the trajectory prediction capability in which they rely upon.**

Note that for strategic de-confliction purposes (i.e., de-conflicting trajectories from several hours up to some minutes in advance, e.g. from 2 hours to 20 minutes) there is a lot of **uncertainty** related to the effective prediction of the final execution of the flight (i.e., adherence of the actually flown aircraft trajectory to its predicted trajectory), which is often referred as ***trajectory prediction errors***.

In STREAM the **same SESAR future CNS capabilities are assumed** (i.e., data-link, 4D-FMS, ADS-B...) that would allow a precise 4D navigation for each flight together with a precise real-time traffic monitoring, whereas the air-ground trajectory predictions will be harmonized (shared by data link) and supported by robust wind and temperature forecasts, thus significantly improving the accuracy and reliability of the trajectory prediction data. Therefore, like in [19], the **uncertainty related to trajectory prediction errors can be trun-**

cated to a maximum look-ahead time (e.g., 20 minutes) about its scheduled trajectory, since it is presumed that tactical trajectory and conflict management tools (e.g., MTCD) will amend (if necessary) any trajectory deviation until the original trajectory (i.e., original 3D path and downstream time restrictions) is reached again, or otherwise will clear a new negotiated RBT.

The presence of convective weather (e.g., thunderstorms) or other sources of uncertainty with deep impact on the strategically generated plans will be addressed via a **real-time reconfiguration of the routes allocated to each flight**. The information on flight intentions and on the current and forecasted status of the entire European network will be available through the NOP, a continuously updated rolling plan that enables a seamless conflict management process running continuously from the strategic phase (pre-departure, collaborative design of the NOP) up to the execution phase (automation-assisted, controller-driven conflict resolution).

A typical scenario at the European level with a planning horizon of 2-3 hours is expected to include up to 5000 simultaneously active flights [88]. The high density and complexity of European air traffic implies a high number of interactions among the different trajectories, especially in those regions with more expected congestion. Thus, **high computational efficiency is required in the CD&R algorithms** for storing and analysing the state-space information of several thousands of trajectories to ensure that the proposed local resolutions do not generate secondary reactive conflicts in other zones of the network (i.e., **the CD&R system must consider potential emergent dynamics in the network for global optimization**).

After the CD&R process, **different conflict-free solution scenarios will be generated**. Each of these feasible scenarios will be weighted according to different performance indicators for efficiency, robustness, fairness and equity [43, 48, 88]. Under all circumstances, a final agreement between the involved service providers and the impacted Airspace Users will be necessary to close the SBT negotiation and implement a RBT for each flight. Thus, during the negotiation process, the Airspace Users may express their preferences according to their business targets, which will be used to identify the most beneficial global solution according to selected commonly agreed metrics, thus formally realizing a multi-criteria global optimization of the network route-structure allocation.

For simplicity purposes, the application of the hemispherical altitude rule (i.e., organization of traffic in oriented Flight Levels) is considered in the European airspace as occurring in the current ATM concept. However, the CD&R tools presented in this dissertation can be adapted to a continuous (i.e., not discrete) vertical usage of the airspace. In addition, the STREAM concept of operations only considers en-route traffic (i.e., from Top of Climb (ToC) to Top of Descent (ToD)), and Direct Routes are applied as a simplification of the Free-Routing concept (the CD&R tools presented are fully compatible with concept of Free Route, but the introduction of this concept requires to have real information about the user preferences, the aircraft performance and the weather forecasts, among other information that has not been available in this research).

3.3 Uncertainty

Since uncertainty is a major issue affecting strategic de-confliction systems, several sources of uncertainty have been addressed in the framework of the STREAM project (see Appendix A.5). However, the strategic de-confliction system presented in this dissertation only considers a simplified categorization of uncertainties.

For instance, the uncertainty related to navigational imprecision and tracking errors, which could be tackled by adding uncertainty buffers to the SBTs/RBTs, and whose final result can be treated as 4D corridors in which aircraft can execute their flights within a high confidence interval (4D-FMS navigation assumed).

Once all the trajectories in the network have been de-conflicted (considering the nominal safety distance plus the extra buffers), unexpected events (i.e., perturbations) can still occur, thus requiring a modification of the NOP. In this dissertation, the perturbations are classified and simplified as:

- *Individual-level perturbations*, referring to those unexpected events caused by the AUs that generally affect only a reduced set of trajectories, e.g., large delays and/or trajectory deviations outside of the uncertainty buffer. The problem of how to address individual-level perturbations is a complex topic that is not covered in this dissertation. However, in general, these issues can be addressed by first identifying the AUs responsible for the produced deviation and forcing them to correct the deviation by applying tactical amendments (the same automated STREAM CD&R algorithms could be adapted to tactical operations) according to the principle of “the one that deviates is the one that pays”.
- *Network-level perturbations*, referring to those perturbations that are independent from the behaviour of the AUs and generally affect a large set of trajectories or even the entire network, e.g., convective weather and volcanic ash, among others. In presence of network-level perturbations, such as a dangerous storm that forces the NM to close certain (demanded) airspace sectors, the complete network route allocation must be reconsidered.

> Again, the AUs may provide the NM with their preferred SBTs/RBTs by considering the most updated information on the state of the network. If the CD&R tools applied are sufficiently rapid, then the NM can provide a new airspace configuration/route allocation adapted to the AU preferences that is subject to the changing network restrictions in real-time (see Article 2 on page 155). According to the STREAM ConOps, an acceptable look-ahead time horizon for the NOP would be approximately 2 hours and the updating frequency less than a minute.

Note that the strategic de-confliction system proposed in this research is compatible with the current tactical surveillance and management of conflicts as well as with the on-board collision avoidance systems (i.e., TCAS). Thus the air traffic can be protected by three different layers of conflict management (i.e., strategic, tactical and operational) that may reduce the negative impact of uncertainty in the ATM safety levels.

3.4 STREAM Assumptions

The main assumptions upon which the STREAM solution for conflict detection and conflict resolution relies are:

- Airspace Users are capable of submitting the SBTs and RBT updates (sent from aircraft via data-link) for all the flights they are planning to operate or they are actually operating within the European airspace, with at least 2 hours of trajectory prediction look-ahead.

- The NM has the technical capability of receiving the SBT requests and RBT updates from AUs, performing the necessary data pre-processing to data parsing and insertion into the SDS.

- The Airspace Users and the NM have all the systems in place enabling the iterative negotiation of 4D Trajectories from the strategic phase up to the execution one (i.e., from SBT definition up to the agreement and updating of the RBT).

- Different levels of weather forecast accuracy are achievable according to the time horizon and the variable forecasted. The STREAM solution will be tested under several different conditions in order to explore the potential performance of the algorithms. In particular the project will assume different levels of Trajectory Prediction (TP) performance to study the feasibility and potential benefits of STREAM, with weather forecasts (mainly wind and temperature) being a key factor for the TP performance.

- The information in the SDS is maintained constantly updated by the NM, by periodically reflecting the status of the RBTs already on execution, as well as registering their deviations and also allowing to compare the SBTs of flights still on the ground with the most updated picture of current and estimated future traffic situation in the SDS.

Additionally a number of additional assumptions are also relevant, although not directly impacting the STREAM implementation, but rather for guaranteeing that the trajectory strategic amendments proposed by the conflict resolution module are later achievable during the execution phase:

- 4D Trajectory Datalink Services (4DTRAD) are fully implemented and usable by ground and airborne systems. This allows data exchange and coordination between air and ground during the execution phase, permitting ATCOs to assess the compliance of aircraft with the agreed RBTs and to react to changes according to a specified TMR.

- All aircraft are 4D-FMS equipped thus being able to receive and automatically load in onboard navigation system multiple constraints (including several time constraints) that will be executed with enough precision.

- P-RNAV operations are available at European airspace level and all aircraft have RNP-1 navigation capabilities, thus 1NM mile of horizontal deviation from the RBT might be allowed.

- The European en-route airspace is considered to be organized through the semi-circular cruising levels system, even if Free Route operations are considered [41]. Thus, aircraft are vertically separated with the current safety standards (i.e., 1000 ft since Reduced Vertical Separation Minima applies) and thus vertical deviations/overshots around 200 ft could be acceptable.

- ADS-B is fully operative in all aircraft, enabling ASAS and TCAS functions. The ASAS system allows the precise self-separation and syncronization of aircraft, while the TCAS system empowers a last safety layer to avoid collisions in case that both strategic and tactical conflict management fails (i.e., safety nets).

- Uncertainty related to trajectory prediction errors can be truncated to a maximum look-ahead time (e.g., 20 minutes) about its scheduled trajectory [19], since it is presumed that tactical trajectory and conflict management tools (e.g., MTCD) will amend any trajectory deviation (if necessary) until the original trajectory is reached again.

- Network uncertanties which may cause important losses of capacity at any sector or airport are not considered/not explored in the nominal traffic model (although the design of the algorithms has considered a fast updating rate in order to allow a fast re-configuration of the network route allocation).

- Only en-route traffic is considered in the nominal traffic model (i.e., from ToC to ToD).
- Direct Routes (geodesic or loxodromic paths) are applied as a simplification of the Free-Routing concept.

3.5 Summary of the CD&R Main Features

3.5.1 System Architecture

The CD&R system architecture developed for the STREAM project is illustrated in Fig. 3.3. This architecture together with the system logical functionality has been also detailed in the Article 5 (page 205 of this dissertation).

The inputs of the system are a set of SBTs/RBTs published by airlines as well as selected extra information on the current state of the ATM, e.g. airspace availability and configuration. Note that for real operational purposes these inputs should be obtained through the SWIM communication platform. A proof-of-concept application in which the CD&R system developed for STREAM has been integrated with SWIM can be found in Appendix A.1.

The relevant subsystems of the CD&R system consist of:

- A *Conflict Detection* (CD) module that analyses the different trajectories by means of a Spatial Data Structure (SDS) with a twofold purpose: a) to generate the state-space representation of the network and b) to perform conflict detection
- A *Resolution Trajectory Generator* (RTG) module that solves the conflicts by generating different alternate trajectories (using different types of manoeuvres for each aircraft and conflict) with a local optimization scope (i.e., optimizing each particular resolution trajectory without taking into consideration the potential domino effects with the rest of the network). Each newly generated trajectory is sent back to the CD module and stored in the SDS to generate and store the new state-space information.
- An *Interaction Causal Solver* (ICS) that is tasked with analysing the state-space stored in the SDS (with the original and alternate resolution trajectories) to detect network interactions (i.e., positive or negative domino effects)

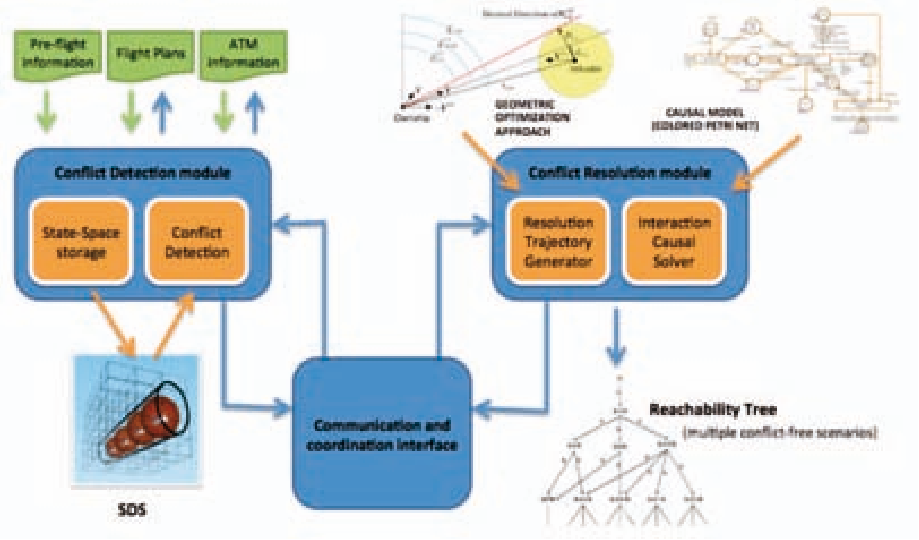


Figure 3.3: STREAM CD&R architecture

The STREAM proposed architecture for the strategic CD&R system consists on three modules that cyclically interact among them. The CD module is enabled by a SDS configured to store all the relevant state variables of the ATM along the considered planning horizon. The CR consist on two sub-modules, the RTG that generates local-optimal resolution trajectories for each detected conflict treated as isolated in the network, and the ICS that analyzes the domino effects of those local-optimal trajecories and finds several conflict-free scenarios (if any exists) through a state-space exploration based on a causal analysis model.The third CD&R module is in charge of managing the information and coordination between the CD and CR modules.

among all of the processed trajectories and to subsequently propose several conflict-free scenarios at the network level. Post-processing could apply metrics to the available feasible solutions to obtain the globally optimal solution scenario.

- A communication interface used to coordinate the CD, RTG and ICS modules.

3.5.2 System Logical Functionality

The system architecture presented in the previous section is applied according to the following steps:

0. A set of user-preferred free-route trajectories is introduced into the CD&R

system.

1. Given a set of trajectories, the CD module detects the conflicts among them. All of the processed trajectories remain stored in the SDS to ease the detection of conflicts among new sets of trajectories and their interactions with previously processed sets.

2. The RTG module generates several locally optimal trajectories per each pair of trajectories and conflicts by considering different restrictions, i.e., different types of manoeuvres used to solve single conflicts, multiple conflicts, to match time-restrictions or to find cooperative resolutions, among others. The *local optimality* of the trajectories is defined by the AUs, who express (directly or indirectly) their preferred alternate SBTs/RBTs for each flight given a set of restrictions provided by the NM through the CD module. Note that the order of conflict processing does not affect the local optimality of the alternate SBTs/RBTs because each pair of trajectories in the conflict are processed at this step and treated as totally isolated in the network, i.e., the optimal AU (local) resolutions are generated with no consideration of other potential interactions with the rest of the trajectories. This assumption is based on the fact that the later causal analysis (step 7) will explore different combinations of potential conflict-free scenarios in which each of the alternate trajectories (that are generated by the RTG in this step) may be considered as valid in at least one scenario (i.e., in at least one combinatorial branch) and, in each case, the rest of the alternate trajectories will be configured around the trajectories already considered valid, also by exploring different combinations of valid alternate trajectories (i.e., trajectories that do not generate conflicts with the previously accepted trajectories in each combinatorial branch).

3. The CD module again evaluates the new set of alternate SBTs/RBTs to detect conflicts among them as well as with the previously processed sets of trajectories. The conflicts detected among different alternate SBTs/RBTs generated for the same flight are discarded (an aircraft will only fly one of its alternate SBTs/RBTs so they cannot be in conflict among themselves).

4. Points 1, 2 and 3 described above constitute a cycle that can be repeated several times to detect and provide resolution SBTs/RBTs to secondary and tertiary emergent conflicts, thus increasing the probabilities of finding final feasible solutions. At the end of this step, a complete 4D representation of the airspace's present and future (expected) states remains stored in the SDS.

5. All of the alternate SBTs/RBTs generated at point 2 per each flight are sorted according to a given order of preference expressed (directly or through

agreed indirect methods) by the AUs. The information taken from the AU preferences will avoid exploration of sub-optimal feasible solutions, thus reducing the exploration of the solution space to the set of *Pareto-efficient feasible solutions.*

6. Causal exploration with constraint propagation involves the following process. The causal model consists of opening a branch of the reachability tree per each SBTs/RBTs and subsequently propagating the constraints by activating/deactivating the set of primary, secondary or tertiary conflicts (extracted from the SDS at step 4) and the availability of the pre-sorted alternate SBTs/RBTs (introduced as input in step 0 or generated by the RTG at step 2). This model takes into consideration all of the possible emergent dynamics (i.e., domino effects), thus achieving *completeness* of the solution space, and at the same time, *reducing the solution space* exploration by focusing on the Pareto frontier of the feasible set of solutions.

7. The computation of online metrics (of efficiency or any other criteria) during the causal exploration and their comparison among the branches that belong to the same level of the reachability tree allows a *driven search* via a hill-climbing/minimal-gradient algorithm, which outputs the feasible final states with better metrics first (i.e., more efficient scenarios are found first).

Note that the order in which conflicts are processed and locally solved by the RTG module (step 2) does not affect the ICS causal analysis used to find global conflict-free solutions (step 6 and 7) because the ICS analyses the overall 4D state-space information stored in the SDS once the CD-RTG-CD sequence (steps 1, 2 and 3) has halted after a (parameterizable) maximum number of cycles (step 4).

3.5.3 Technological Framework for the Conflict Detection Module

Spatial Data Structures have been firstly explored as a technique for implementing a MTCD process (see Article 1 in page 131) with excellent results in terms of time performance due to the linear computational complexity (denoted by O(n)) of the CD algorithms based on SDS [89, 93, 81, 92, 91]. In addition, the use of SDS allows the storage of the entire state-space description of the traffic among all of the processed trajectories at the time when the conflict detection analysis is performed. Causal models can be employed based on the SS information stored in the SDS because all of the processed trajectories (both planned and alternate "what-if" types of trajectories) will remain stored as a "4D snapshot" of the ATM system [89, 93, 92, 90, 81]. See Articles 2, 3, 4 and 5 on pages 155, 183, 193 and

205 respectively.

For the SDS to be adapted for STREAM Strategic De-confliction system requirements, three important innovative concepts were introduced in the SDS structure. Specifically, the design of the Relational SDS (RSDS) concept achieved a reduction of the main memory requirements of more than 98% with respect a “non-relational” SDS for the same ATM scenarios. See Fig. 3.4. The evolution from SDS concept to RSDS concept is further explained in Article 2.

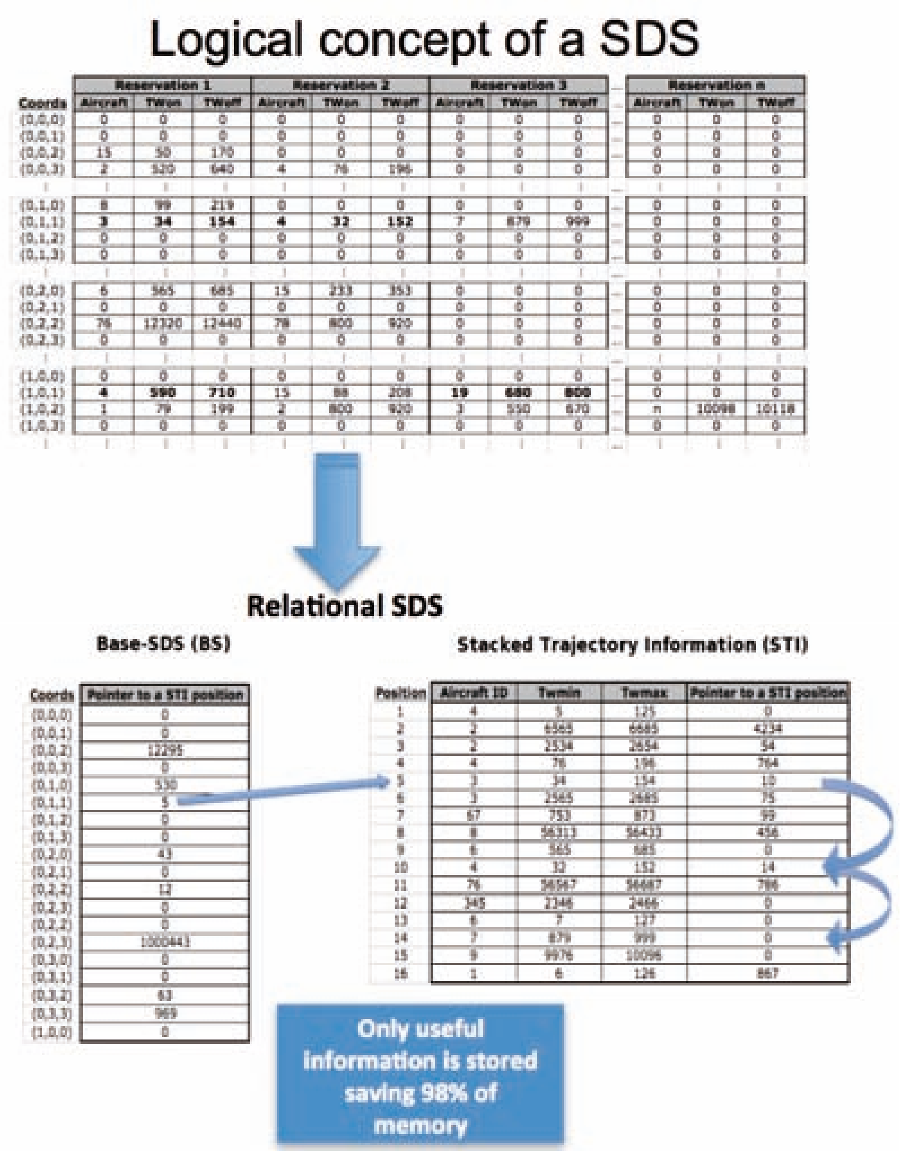
On the other hand, another innovation was also presented: a new dimension was included in the data structure (i.e., Time), thus becoming a Time-Spatial Data Structure (TSDS). See Fig. 3.5. This innovative structure contributed to a better performance in the CD module in most common ATM scenarios, providing the ability of processing thousands of trajectories in few seconds. See Fig. 3.6. More detailed explanations about the TSDS concept can be found in Article 2.

For the Strategic De-confliction purposes of this research the CD process was conducted through a RTSDS (i.e., RSDS+TSDS), which in turn acted as a powerful spatio-temporal pruning filter: for each time-step, the point-mass position of a trajectory is stored in the RTSDS, and a Near-Neighbour Search is done in order to find potential conflicts with the nearby traffic. See Fig. 3.7. In this way, pairwise comparisons are only computed among a reduced amount of trajectory segments. The RTSDS configuration and the Near-Neighbour Search concepts for Strategic De-confliction are explained in deeper detail in Article 2.

It is worthy noting that bins of size equal or bigger than 10NM (i.e., twice the 5NM minimum aircraft separation) mathematically ensure that all the potential conflicts are detected in the nearest 4 bins from the given point-mass position of an aircraft. Based on similar arguments, the vertical plane bin-size was parameterised with 600m.

Finally, a third innovation was introduced in the SDS concept in order to take into account the curvature of the Earth along the European airspace: the shape of the SDS has been evolved from a planar shape to a curved shape. Fig. 3.8 shows a graphical representation of the SDS that has been implemented in the RAM main memory for the strategic CD purposes under STREAM project. Note the variable size of the bins used to perform Near Neighbour Searches (see Article 2 to find detailed examples of Near Neighbour Search usage).

The concept of Geodesic SDS has not been sent to journals for publication. Thus no information is given in the Articles presented in Chapter 4 of this dissertation. However, results presented in Article 2 and Article 5 for scenarios of



Logical concept of a SDS

	Reservation 1			Reservation 2			Reservation 3			…	Reservation n		
Coords	Aircraft	TWon	TWoff	Aircraft	TWon	TWoff	Aircraft	TWon	TWoff		Aircraft	TWon	TWoff
(0,0,0)	0	0	0	0	0	0	0	0	0	…	0	0	0
(0,0,1)	0	0	0	0	0	0	0	0	0	…	0	0	0
(0,0,2)	15	50	170	0	0	0	0	0	0	…	0	0	0
(0,0,3)	2	520	640	4	76	196	0	0	0		0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	…	⋮	⋮	⋮
(0,1,0)	8	99	219	0	0	0	0	0	0	…	0	0	0
(0,1,1)	**3**	**34**	**154**	**4**	**32**	**152**	7	879	999	…	0	0	0
(0,1,2)	0	0	0	0	0	0	0	0	0	…	0	0	0
(0,1,3)	0	0	0	0	0	0	0	0	0	…	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	…	⋮	⋮	⋮
(0,2,0)	6	565	685	15	233	353	0	0	0	…	0	0	0
(0,2,1)	0	0	0	0	0	0	0	0	0	…	0	0	0
(0,2,2)	76	12320	12440	78	800	920	0	0	0	…	0	0	0
(0,2,3)	0	0	0	0	0	0	0	0	0	…	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	…	⋮	⋮	⋮
(1,0,0)	0	0	0	0	0	0	0	0	0	…	0	0	0
(1,0,1)	**4**	**590**	**710**	15	88	208	**19**	**680**	**800**	…	0	0	0
(1,0,2)	1	79	199	2	800	920	3	550	670	…	n	10098	10118
(1,0,3)	0	0	0	0	0	0	0	0	0	…	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	…	⋮	⋮	⋮

Relational SDS

Base-SDS (BS)

Coords	Pointer to a STI position
(0,0,0)	0
(0,0,1)	0
(0,0,2)	12295
(0,0,3)	0
(0,1,0)	530
(0,1,1)	5
(0,1,2)	0
(0,1,3)	0
(0,2,0)	43
(0,2,1)	0
(0,2,2)	12
(0,2,3)	0
(0,2,2)	0
(0,2,3)	1000443
(0,3,0)	0
(0,3,1)	0
(0,3,2)	63
(0,3,3)	969
(1,0,0)	0

Stacked Trajectory Information (STI)

Position	Aircraft ID	Twmin	Twmax	Pointer to a STI position
1	4	5	125	0
2	2	6565	6685	4234
3	2	2534	2654	54
4	4	76	196	764
5	3	34	154	10
6	3	2565	2685	75
7	67	753	873	99
8	8	56313	56433	456
9	6	565	685	0
10	4	32	152	14
11	76	56567	56687	786
12	345	2346	2466	0
13	6	7	127	0
14	7	879	999	0
15	9	9976	10096	0
16	1	6	126	867

Only useful information is stored saving 98% of memory

Figure 3.4: Evolution of the SDS towards the Relational SDS concept

The logical architecture (i.e., disposition of the inner computer memory and information access methods) of the SDS has been evolved based on the Relational Database concepts in which different database tables and records are linked through pointers/key fields. This new treatment of the information has allowed to save more than 98% of the memory necessary to save and manage the same ATM scenario with respect the original SDS logical architecture.

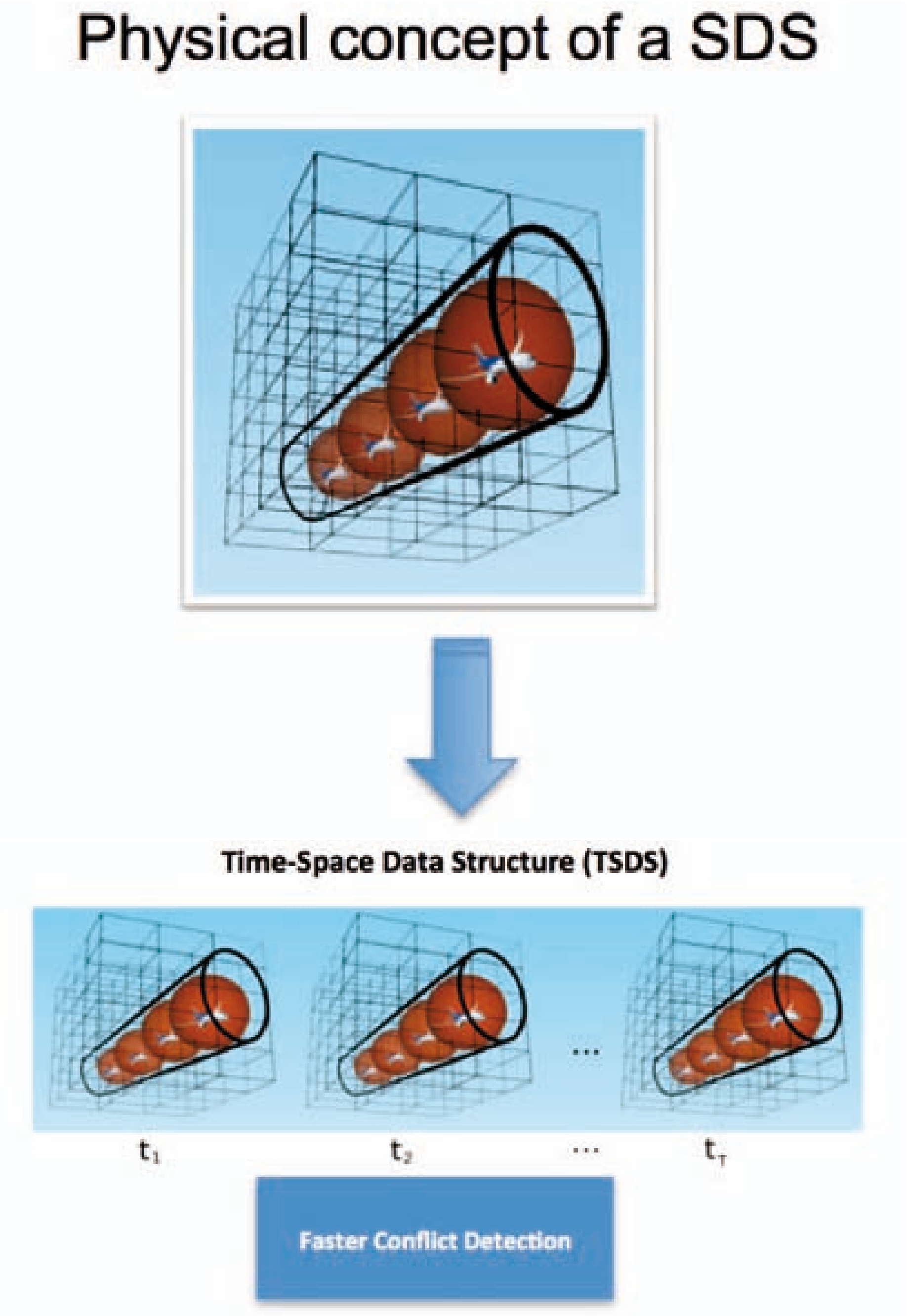


Figure 3.5: Evolution of the SDS towards the Time-Space Data Structure concept

The physical concept and the data structure (i.e., disposition of the inner database records) of the SDS has been evolved to consider not the spatial information but the spatio-temporal information intrinsic to a 4D ATM model. The concept requires adding an additional non-spatial dimension, i.e., the time, to the Data Structure, thus the information must be read/written by pointing to a database record that represents a certain 4D coordinate of the ATM (i.e., the 3D coordinates in different times are considered to be different ATM resources).

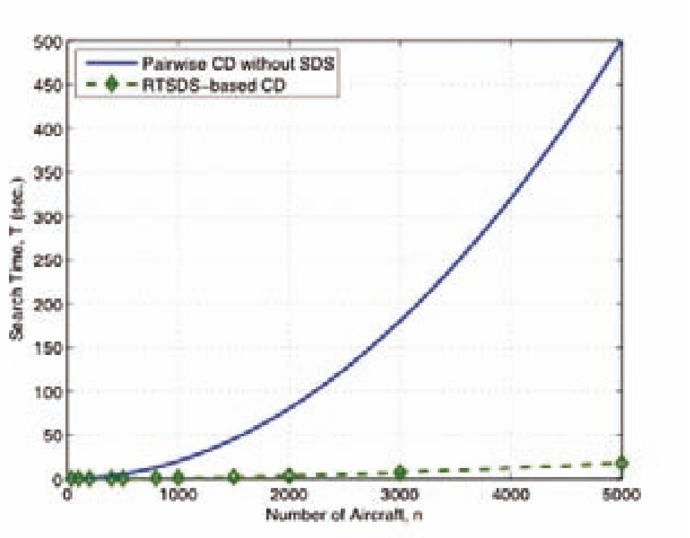


Figure 3.6: Performance comparison between a pairwise CD without filters and a CD based on RTSDS utilisation

Simulations have shown that the use of a RTSDS can speed up the CD process more than 3000% in the case of 5000 trajectories with respect a CD algorithm that does not apply any kind of filter to avoid unnecessary pairwise comparisons.

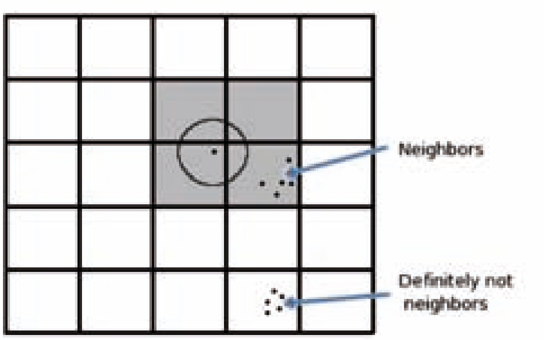


Figure 3.7: Near-Neighbour Search applied to filter some pairwise comparisons

The detection of conflicts is performed for each flight trajectory by, first, identifying at each time step which are the neighbours (i.e., aircraft geographically correlated at close locations) in order to filter the amount of pairs to be compared with and, later, checking the sptatial distances amongh those remaining pairs of trajectories. A neighbourhood (shadowed bins in the figure) is defined by geometrical arguments (see Article 2 on page 155 for details).

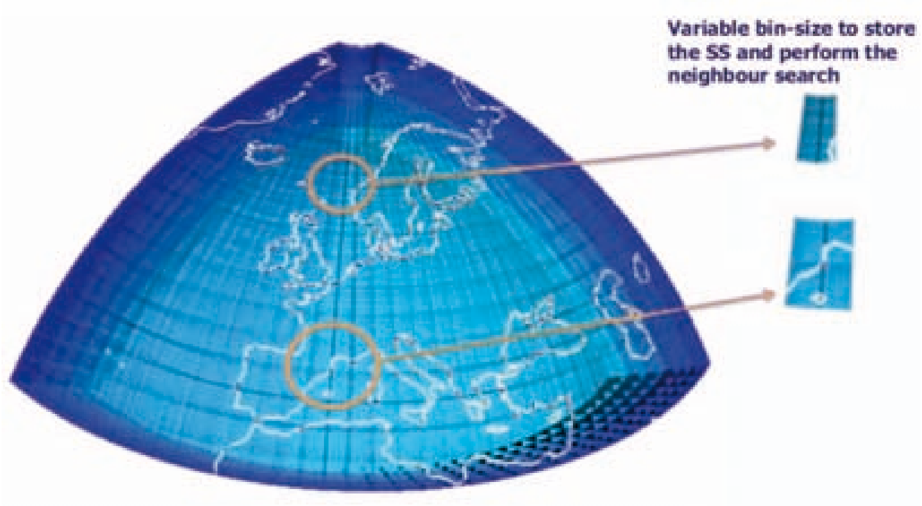


Figure 3.8: Approximate shape representation of the Geodesic SDS applied for strategic CD&R over European ATM

The dimensions of the European ATM scenario require to adapt the SDS concepts in order to consider the curvature of the Earth. The Geodesic SDS concept is based on the utilization of constant bin-separation in terms of latitute and longitude degress, which implies a variable bin-size in different areas of the scenario. See Appendix A.3 for more details.

continental size, both requiring the consideration of the curvature of the Earth, made use of the Geodesic SDS. Appendix A.3 gives additional details about how the SDS can be adapted to consider the curvature of the Earth.

3.5.4 Technological Framework for the Conflict Resolution Module

The initial version of the CR module consisted on a standalone module that was in charge of finding feasible conflict-free solutions at global/network level. The trajectory amendments were based on the identification of an area of conflict between two trajectories and the computation of off-set deviations with a starting point of the manoeuvre a few minutes before the time of conflict, and an end point a few minutes after the last time of conflict. See Fig. 3.9.

In some cases, a manoeuvre that is intended to solve a conflict can generate other conflicts that previously did not exist in the ATM network. These network effects are called interactions, and they have been classified in this research as follows (see Fig. 3.10):

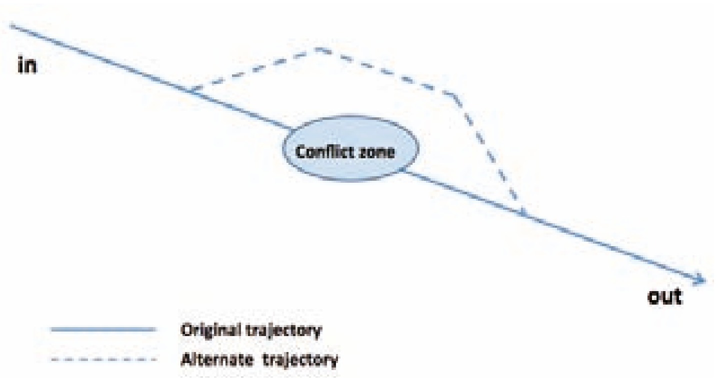


Figure 3.9: First CR strategies to find conflict-free trajectories

> *The first version of the CR module developed in STREAM was based on the calculation of trajectory off-sets that solved the individual detected conflicts and through a trial-and-error strategy several global feasible solutions could be found when a reduced set of trajectories was considered. This approach suffered of several shortages, such as the huge number of request-answer interactions required between the CD and CR modules or the partial consideration of the domino effects generated by the resolution amendments.*

- *Primary conflict*: a conflict between two original SBTs/RBTs
- *Secondary conflic*t: a conflict that emerges between a resolution manoeuvre proposed by CR to solve a primary conflict and a surrounding original SBT/RBT.
- *Tertiary conflict*: a conflict that emerges between two resolution manoeuvres belonging to any surrounding aircraft.

Any trajectory, either an original SBTs/RBTs or a resolution trajectory proposed by the CR, may have more conflicts after their first encountered conflict, which is referred as downstream conflicts. Note that a resolution trajectory generated for solving a conflict between two SBTs/RBTs could generate network interactions that previously did not exist. Also note that resolution manoeuvres could also solve original downstream conflicts that existed before in the original SBT/RBT. These new interactions appearing in the network (or the elimination of pre-existing interactions) are sometimes called “domino effects” or, more formally, network effects [69]. When a trial resolution trajectory generates new network interactions it is referred as a *destabilizing effect*, and when they indirectly solve downstream conflicts it is referred as *stabilizing effec*t. In [61, 66] the Authors underline the importance of taking into consideration these domino effects in the design of a CR system, since these phenomena notably affect the quality of the

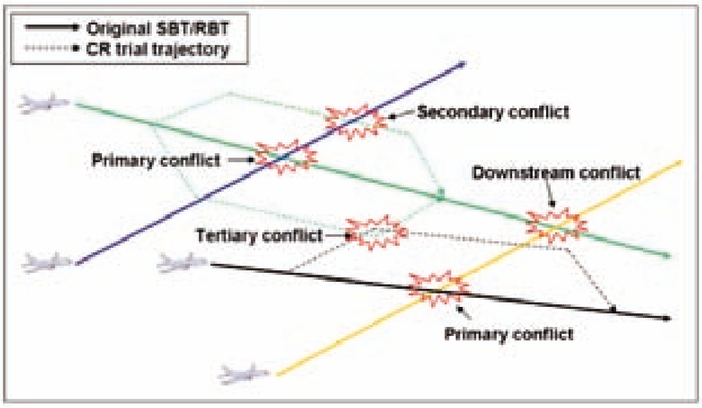


Figure 3.10: Domino Effects emerged among the original and amendmed trajectories

> *Three different kinds of interactions among trajectories have been considered in this research, i.e., primary, secondary and tertiary conflicts, according to whether the conflicts appear between two original trajectories, between a resolution trajectory and an original one, or between two resolution trajectories, respectively.*

resolutions from the network point of view.

In order to find global conflict-free solutions, the CR module conducted a *trial and error search* until a set of feasible solutions were found. However, note that this first version of the CR considered only partially the domino effects occurred as a consequence of the local trajectory amendments, since it was able to deliver global conflict-free solutions but had not into account any kind of local or global optimization. See in Fig. 3.11 an example of a feasible solution (not necessarily optimal).

Since the architecture under consideration (see Fig. 3.3) allows a high degree of independency between the CD and CR modules, a lot of flexibility is available for changing/improving the CR module. Due to the **importance of considering the domino effects in the CR module**, the following changes has been introduced in the system:

1. **Find analytical forms to efficiently compute resolution trajectories** and use a causal model to explore the emergent dynamics: the CR module has been divided in two sub-modules. One of them based on a mathematical geometrical approach to calculate resolution amendments and the other based on causal modelling to deal with the underlying cause-effect interactions of domino effects.

2. **Avoid conducting trial-and-error state-space analyses** to find global conflict-free solutions. The huge amount of trajectories and conflicts to be managed at European ATM level makes the trial and error search impractical, given the big computational burden required. The current causal model implemented in the ICS module takes advantage of the state-space information generated and stored in the SDS and applies causal exploration to divide the problem into unconnected clusters and also to reduce the set of scenarios to be analysed to the Pareto-frontier of the feasible solutions.

3. **Reduction of information transmission**: again, the huge amount of information to be transmitted between the CD and CR modules has forced to change the communication interface (previously through an external database) and substitute it by a complete integration of all the modules and sub-modules in the same C++ application. The new interface includes an efficient trajectory identification method based on modular arithmetic (see Appendix A.2).

To cope with the above limitations the CR has been divided in two sub-modules: the RTG and the ICS. The main purpose of the RTG module is to compute new optimal alternate trajectories for each aircraft in conflict (and for each conflict if an aircraft is involved in more than one). Ideally, the RTG module could support AUs defining their own preferred alternate flight plans in response to a set of restrictions imposed by the NM generated in order to synchronize the traffic and avoid the conflicts. This user-defined local optimality of the resolutions (that meet the network and flow constraints) can then be used by the ICS module to reduce the solution space search and to find global-optimal solutions. For simplicity, in this research the generation of these user-preferred resolution trajectories is based on (and substituted by) a Geometric Optimization Approach (GOA) algorithm [8, 51].

The advantage of the GOA model is that it takes into account the geometric characteristics of 2 aircraft trajectories that are in conflict in a relative framework (see Fig. 3.12), and applies a set of **closed-form analytical expressions** to find the required conflict avoidance commands for each of the flights. This technique allows to solve the conflicts through the application of different kind of manoeuvres such as Heading Angle Changes (HAC), Speed Changes (SC), Flight Level Changes (FLC) or a combination of them in a cooperative or non-cooperative mode. These resolutions are called “optimal” in the sense that they minimize the velocity vector changes with respect the original trajectory.

Figure 3.13 shows one example scenario solved with the first CR version (left), and the same scenario using the new CR with the GOA approach (right) in which the “local optimality” of the new RTG amendments can be observed. Note that

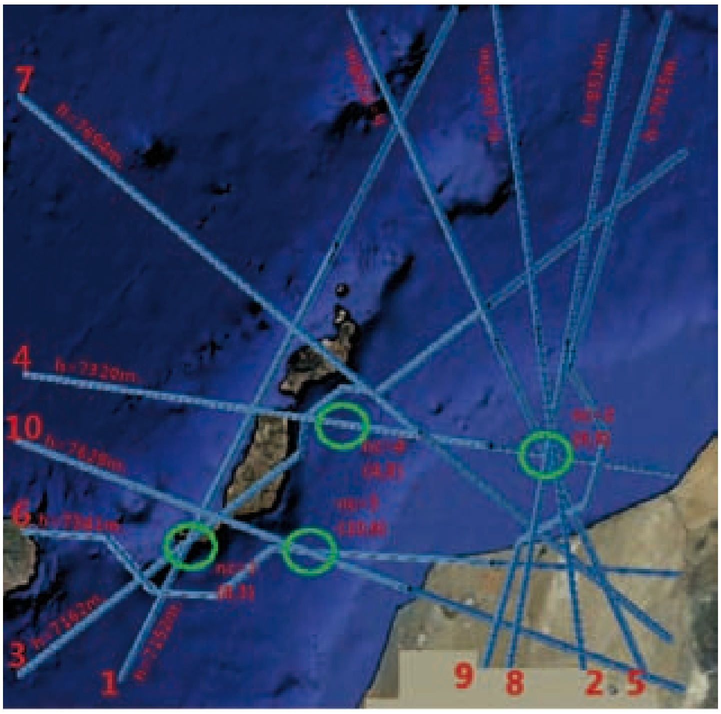


Figure 3.11: Conflict-free scenario delivered by the first CR module version

The first CR version was oriented to find feasible global conflict-free solutions, but with no consideration of the global or local optimality of the proposed resolution amendments.

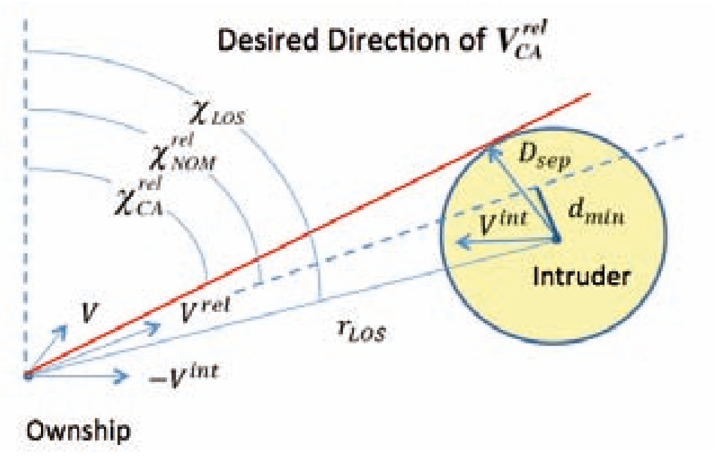


Figure 3.12: Relative geometic framework to find analytical solutions through a Geometric Optimization Approach

The Geometric Optimization Approach algorithm is based on the stablishment of a relative geometric framework which takes into consideration the relative speeds and finds optimal solutions in the sense that minimize the velocity vector changes during the resolution maneouvers.

the resolution manoeuvres of the previous CR version were based on a trial and error search and used a more “tactical” approach, i.e., a CR system performing at tactical level usually takes as input conflicts predicted in a look-ahead time of 20 minutes, while the resolution amendments usually are calculated to start 6-10 minutes before the predicted conflict and finish at any waypoint specified in the original route/RBT. However, the sooner the resolution amendment is started, the softer is the trajectory change, and thus the closer is the new trajectory to the RBT. Therefore, in a CR that is set to perform at strategic level, the resolution manoeuvres can be anticipated and incorporated in the flight plan as a new route, i.e., the CR at strategic level can act as flight route planner/re-planner (note that aircraft could be or still not be airborne when the strategic de-confliction is applied). The GOA approach has been implemented as a sub-module of the new CR version (presented in this dissertation) and adapted to take full advantage of the strategic perspective (see Appendix A.4), i.e., allowing the resolution amendments to start and end at the origin and end points of the trajectories, thus minimizing the velocity vector deviation with respect the original SBT/RBT.

Considering the SESAR 2020 ATM technological framework [101, 105], it might be possible to ignore the current ATM structure of routes [7]. Ideally, Free Routing shall be considered instead, although **in STREAM the Free Route concept has been simplified and substituted by Direct Routes (i.e.,**

geodesic path between two coordinates) from the ToC and the ToD points and subject to the current semi-circular cruising level system [41] (ideally the starting and end points of the resolution manoeuvres should coincide with the beginning and end points of the RBT, i.e. gate to gate). Note that **other ways to obtain optimal/user-preferred resolution trajectories could be also compatible with the STREAM concept**, e.g., introducing more complex and advanced resolution algorithms that better exploits the concept of free routing (e.g., taking advantage of favourable wind flows, minimizing en-route charges, etc.). Cooperative resolutions could be also accepted since the STREAM solution works at strategic/pre-tactical level thus generating a dynamic route allocation within the European ATM rather than reacting to near-term or medium-term conflicts.

Besides to the “local optimality” of the resolution amendments, another important advantage of using the GOA analytical framework in the RTG module is that, given a kind of resolution manoeuvre for one of the aircraft in conflict (e.g., heading change, altitude change, speed change, and so on), **it is possible to determine with little computational and time effort if there is a feasible resolution or not** rather than exploring the state-space with a trial-and-error search (ideally, it is expected that Airspace Users could apply a similar analytical approach if they were requested to calculate their preferred trajectories to feed the CD&R system). Thus, thousands of trial trajectories can be efficiently generated with the GOA analytical framework and sent to the CD, which in turn this module will provide feedback about the network interactions of these new generated trial resolution trajectories. This state-space feedback information can be given by the CD module thanks to the data framework supported by the SDS, and thus this information can be analysed by the causal model that is implemented in the ICS module.

Note, however, that **adapting the GOA algorithm for the strategic deconfliction of trajectories at European continental level has required dealing with some major limitations**, i.e., the original GOA algorithm has been designed for planar geometry and assumes straight lines (constant course lines) rather than geodesic lines (variable course curved lines). Appendix A.4 gives more details about how original GOA algorithm has been modified and adapted to consider the curvature of the Earth and also about other aspects required for strategic trajectory de-confliction such as to solve conflicts between asynchronous trajectories.

With regards to the **technological framework of the ICS module**, a new causal model has been designed and implemented to **take into consideration the upstream/downstream effects** (i.e., domino effects) of the local resolution

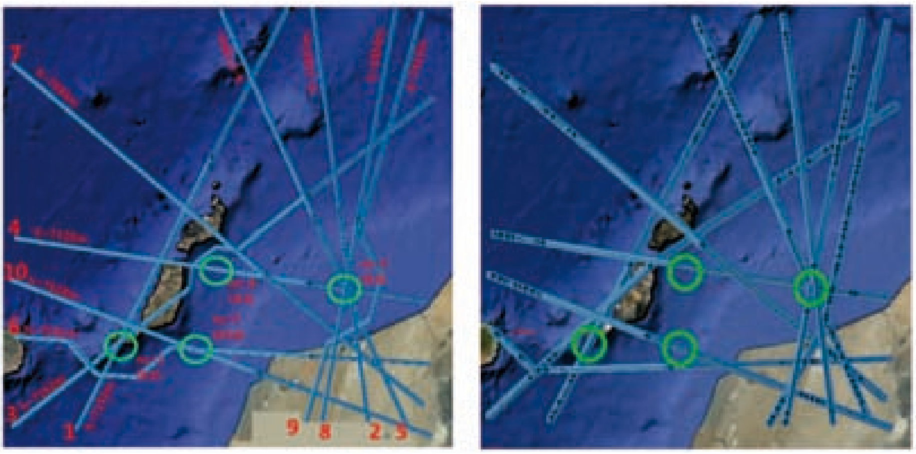


Figure 3.13: Comparison between resolutions of the first and final version of the CR module

> Example scenario solved with the first CR version (left), and the same scenario using the new CR with the GOA approach (right) in which the “local optimality” of the new RTG amendments can be observed.

amendments proposed by the RTG. Once generated by the RTG, the amended trajectories are first analysed by the CD module in order to detect potential new conflicts with the rest of traffic on the network (i.e., destabilizing interactions), or to detect the indirect resolution of previous downstream conflicts (i.e., stabilizing network effects). After one or several feedback cycles[1] in which the CD module processes the alternate/resolution trajectories proposed by the RTG and returns information about the potential emerging conflicts, the ICS takes the updated information from the SDS and, by means of a causal analysis, it finds and delivers several conflict-free scenarios (i.e., feasible final states) that can be compared and assessed by human operator to determine the preferred option to be enforced.

This kind of conflict resolution problem with optimization at network level is a **Non-Polynomial combinatorial problem** [16] that cannot be solved by comprehensevely exploring all the state-space (i.e., “brute force”). In this research, several strategies have been addressed to analyse the optimization problem of the strategic de-confliction while dealing with the exponential growth of the state-space. Such techniques have been documented in the published Articles 4 and 5 (respectively on pages 193 and 205).

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[1] In the simulations performed in this reseach (Chapter 5 and Article 5 on page 205) only one CD-RTG-CD cycle has been considered, however already obtaining excellent results.

These techniques have permitted reducing the size of the problem to a treatable one, relying on: first, desiging a causal model to properly represent the underlying emergent dynamics of the system, second, finding strategies for reducing the problem to a set of multiple unconnected sub-problems known as *clusters*, and finally, reducing the exploration to the **Pareto frontier of a multicriteria optimization function**.

The causal model can provide **optimal or near-optimal solutions** for clusters with a relatively small number of trajectories (clusters of the order of a few dozens or more can still result intractable in practice). At the end of the ICS process, several combinations of conflict-free solutions are delivered. With the computation of different metrics to measure efficiency, safety, robustness, equity and fairness, among other criteria, it would be possible to determine which of the feasible conflict-free solutions is the most preferred for all the airspace stakeholders.

In order to not deliver an unpractical amount of feasible solutions for evaluation purposes, a **minimum gradient search** can be introduced in the causal model. Thus, the ICS can be restricted to deliver a maximum amount of feasible solutions, e.g. 100 feasible solutions, thus delivering the first 100 feasible solutions that also would be the 100 conflict-free solutions with the minimum cost (according to a certain metric). The metric used for the minimum gradient search might be different than the cumulated cost used for simplification in this research.

Chapter 4

Guidance and Chronology of the Published Articles

Five articles have been included in this dissertation that have been anonymously peer-reviewed by experts in the ATM field before being accepted for publication in journals and/or congresses of recognized quality (see Chapter 7 and the *SESAR Young Scientist Award 2012* certificate in Appendix B in which the quality of these scientific contributions to the ATM is recognized). These articles have been sorted according to the chronological order of the findings presented, which in turn is congruent with the line of argument of this dissertation:

Article 1, "*A Medium Term Conflict Detection and Resolution system for Terminal Manoeuvring Area based on Spatial Data Structures and 4D Trajectories*" (on page 131), has been published in the journal of Elsevier Transportation Research part C. The content of this paper is presented as the seed of the technological framework that has been developed for the Strategic De-confliction system presented in this dissertation. In the paper it is presented a MTCD system that uses time-based separations to dynamically synchronize the traffic that enters into a TMA and start the approach and landing phases. One of the main contributions of this paper is the introduction of Spatial Data Structures as a way to efficiently manage and store spatial information. The SDS allows having a complete 4D description of the TMA sector, thus taking into account the entire planned/expected trajectories of the arriving flights. So, decisions can be efficiently made in real-time with a (potential) coordination among different Decision Support Tools (e.g., AMAN/DMAN).

Article 2, "*Relational Time-Space Data Structure To Enable Strategic De-Confliction with a Global Scope in Presence of Large Number of 4D Trajectories*" (on page 155), has been published in the Journal of Aerospace Operations. It presents two technological innovations applied to the SDS concept presented in previous paper in order to enable and set the usage for the strategic de-confliction of thousands of trajectories at the European airspace. One of the main shortcomings of the SDS presented in Article 1 was that it needed a lot of computer main memory, which made difficult the usage of the same SDS concept for wider airspace sectors and larger number of trajectories. In this paper the Relational SDS (RSDS) concept is presented, which modifies the internal logical architecture of the SDS (i.e., how the SDS allocates the bytes of memory to store the ATM information), and thus achieves reductions of more than 98% with respect the memory needs to store the same ATM information in the original SDS. A second concept, the Time-Spatial Data Structure (TSDS), has added the time in the structure of the SDS, which has represented an important qualitative shift of the concept and has notably improved the efficiency of the SDS during the processing of thousands of trajectories for strategic de-confliction purposes. Note that the problem presented in this paper (i.e., Strategic De-confliction) is different to the problems tackled in Article 1 (i.e., tactical time-based separations), thus the SDS configuration (i.e., which ATM information is stored and how) and methods used during conflict detection process must be also different.

Article 3, "*Computational Efficient Conflict Detection and Resolution through Spatial Data Structures*" (on page 183) has been published in the International Conference on Research in Air Transportation (ICRAT). It highlights the importance of the SDS to keep stored a (pre-configured) ATM micro-model framework in which the complete 4D (or nD) representation of the ATM state (i.e., current state and its expected evolution over the time) can be efficiently stored and managed. Several applications of interest that use the available 4D information of that framework are presented, including the computation of temporal looseness among trajectories, the anticipation of emergent dynamics/domino effects, and the identification of network hot-spots. An empirical demonstration has been also included in order to show how the information available within the SDS can be used by a conflict resolution module (based on a causal model) in order to find global optimal solutions. Note that the scenario presented for the simulations is a congested tactical scenario (30-minute flight segments freely crossing an ATC sector), which was used as an intermediate step to the final European-level strategic de-confliction tool.

Article 4, "*Causal Decision Support Tools for Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management (STREAM)*" (on page 193), has been published in the SESAR Innovation Days (SID) conferences. It presents the advances achieved in the use of the ATM 4D information available through the SDS by integrating an improved version of the conflict resolution module based on causal modelling to deal with the emergent dynamics of the air traffic system. This paper gives details of the conflict resolution algorithm specified in Coloured Petri Nets and presents some of the preliminary results found at that moment during STREAM project execution. In addition, an important strategy to deal with the highly interactive European network with more than 4000 trajectories crossing European airspace at certain peak hours of traffic is also presented, the Clustering causal model, which allows reducing the global problem to a set of unconnected sub-problems, thus considerably reducing the combinatorial state-space search of the problem and the time required to solve it.

Article 5, "*Strategic de-confliction in the presence of a large number of 4D trajectories using a causal modeling approach*" (on page 205), is at the moment of writting these lines in a "conditionally accepted" state in the journal of Elsevier Transportation Research part C. It gives detailed information about the final architecture and logical functioning of the CD&R used in STREAM. It also describes in detail the causal model applied in the conflict resolution module, which works in a and cyclical way with the SDS. Final results of the STREAM project (complementary to the results presented in Chapter 5) after the strategic de-confliction of a nominal scenario with more than 4000 trajectories flying within the European airspace can be also found.

Chapter 5

Scenario Design, Simulations and Discussion of Results

This chapter presents the results of the performance assessment of the Strategic De-confliction algorithms that has been developed in this research for the STREAM project. The initial assessment is based on the nominal synthesized trajectories of realistic European traffic scenarios, thus assuming no relevant TP errors and no Expected Time of Departure (ETD) uncertainty (i.e., assumed perfect pre-departure predictions), neither other sources of uncertainty, for the look-ahead time of the scenario. Posterior assessment introduces TP errors and ETD delays in order to analyse the robustness of the algorithms presented.

5.1 Strategic De-confliction of European Traffic Scenarios

As presented in the Article 5, (on page 205) several simulations were executed applying the real air traffic demand data of a yearly peak traffic day (July 1st 2011) provided by EUROCONTROL and simulated with a precise Trajectory Predictor developed by Boeing Research & Technology Europe (BR&TE) to obtain the Direct Routes corresponding to such set of trajectories.

Taking as input the original airports demand of each historical flight plan, a realistic trajectory was synthesized for each user-preferred 4D trajectory (assumed Direct Routes). These trajectories represent the hypothetical “truthful” trajectories that would be flown if the aircraft were left to fly according to their preferences and assuming no ATM intervention during the execution phase. The resulting trajectories were used as the reference baseline for the final assessment of the CD and CR algorithms presented in this dissertation. The trajectories were synthesized using BR&TE's high-fidelity Trajectory Prediction system. An overview of this infrastructure can be found in Deliverable 4.2 generated as part of the documentation of STREAM project [48]. The synthesized trajectories have been calculated emulating the trajectory planning process of a Flight Management System (FMS) and they include detailed aircraft state information (Lat/Long position, velocities, weight, etc.) at 1-second intervals. These trajectories have been synthesized from departure to destination, including the climb and descent phases. However, only the cruise phase has been considered for the application of the de-confliction algorithms, i.e. from Top Of Climb to Top Of Descent.

The resulting en-route trajectories were cropped to fit within a spatial region covering most of the European airspace as defined with the latitudes in the interval [30, 70], the longitudes in the interval [-20, 30] and the flight levels from FL130 to FL430. A time-window filter corresponding to two hours of maximum airspace demand during the day (i.e., from 16.00 to 18.00) was also applied to the computed trajectories. The resulting scenario included 4010 trajectories with an average length of 32.5 minutes.

Results presented in Article 5 are based on loxodromic Direct Routes (i.e., constant course path between two fixes). In this Section some additional results obtained from the final scenarios used at the last stages of the STREAM project are also presented. These scenarios share similar characteristics (i.e., 4010 trajectories over the European airspace) but the Trajectory Predictor of the FMS was configured to fly geodesic Direct Routes (i.e., shortest path with variable course between two fixes) instead of the loxodromic Direct Routes. Surprisingly the number of detected conflicts is considerably different between the two scenarios, being notably lower in the case of geodesic trajectories.

In addition, two different parameterization versions of the CR algorithm have been applied during the simulations, whose only difference between them is the minimum inter-aircraft separation (composed by the nominal 5 NM separation plus a buffer) applied by the CD&R system to assume that a predicted conflict will be actually resolved:

- Separation of 7 NM (referred to as the 7NM CR version), thus applying a 2NM buffer to the nominal 5NM separation.
- Separation of 10 NM (referred to as the 10NM CR version), thus applying a 5NM buffer buffer to the nominal 5NM separation.

The selection of these two buffers (i.e., 2 NM and 5 NM) is fairly arbitrary at this stage of development (40% and 100% of nominal safety distance) and their main purpose in this document is to illustrate a sensitivity analysis conducted by using different algorithm parameterizations. The ATM insight generated may contribute to the designing of more efficient and robust traffic scenarios.

The result of applying the CD&R algorithms has been a single set of conflicts detected and two different sets of trajectory amendments to solve the detected/predicted conflicts (i.e., one for each CR parameterization version). The trajectory amendments have mainly consisted in changes applied to the original planned path route although in a certain few cases changes in the planned cruise flight level have been also applied. For each of the versions of the algorithm, the CR has assigned trajectory amendments to different sets of flights in the scenario. The two new sets of 4010 de-conflicted trajectories generated from the 7NM and 10NM CR versions have been re-synthesized again by the Trajectory Predictor and processed again by the CD module in order to verify the effectiveness of the Strategic De-confliction algorithms.

It must be pointed out that the CD&R algorithms presented in this dissertation and the Trajectory Predictor developed by BR&TE have been designed and developed independent of each other. Thus, as it often occurs with independent and heterogeneous systems, they assume different models and types of data that can generate imprecisions when sharing information among them. Specifically, the CD&R algorithms that have been introduced in this dissertation use a spherical Earth model (i.e., the standard FAI sphere) whereas the TP tool uses the ellipsoidal Earth model WGS84. These discrepancies cause as a consequence that the covered distances calculated by the CD&R to solve the conflicts and the covered distances "flown" by the TP are approximate but not equal, thus causing some de-synchronization effects that sometimes can lead to the ineffective resolution of some conflicts (see Sub-Section 5.5.2). Trajectories were adjusted during the data processing (varying the cruise speeds as necessary to synchronize the trajectories duration) to reduce the errors to the maximum extent possible but the model uncertainties were still present.

Finally, a diverse set of experiments have been conducted to explore the robustness of the CD&R algorithms in the presence of some sources of uncertainties (i.e., trajectory prediction errors and ETD delays) as well as to explore some basic strategies that can contribute to the achievement of more stable/robust network plans.

5.2 Description of the CD Process

Several simulations have been executed with the (geodesic) trajectories obtained from the application of Direct Routes to the nominal baseline scenario described in previous section. Once the 4D trajectories (sampled every 1 second) have been introduced as inputs for the CD&R system, they have been processed by the CD module and stored in the SDS. A total number of 211 conflicts have been detected among the original trajectories.

Note that the number of conflicts obtained with the application of orthodromic trajectories (i.e., 211) is considerably smaller than the number of conflicts obtained with the loxodromic trajectories (i.e., 325). No explanation has been found to explain such important reduction of conflicts found except that it could have happened by chance. However, this fact seems to be associated to the intrinsic characteristics of the European traffic patterns under consideration, thus it might contribute to justify some ATM policies such as to boost the implementation of modern flight navigation systems to fly geodesic routes.

In the same direction, the 4010 trajectories of the nominal scenario have been also synthesized following the original (structured) routes as provided in the scenario data from EUROCONTROL. The number of conflicts found has been 386 while the average track distance flown by each flight has been around 7% longer than with the application of geodesic Direct Routes. Thus, these findings also justify the application of geodesic Direct Routes at European level.

Another important piece of information to remark about the simulated scenarios is the distribution of the detected conflicts into clusters of different sizes since such distribution determines the complexity of the CR process. Figure 5.1 shows the clustering statistics for the nominal scenario. It can be observed that it follows a negative exponential shape in which most of the clusters involve only 2 aircraft (i.e., easiest case to find locally-optimal solutions) and that more than the 98% of the clusters are composed by less than 7 aircraft. The causal analysis in the CR process (i.e., ICS module) is able to find solutions very efficiently (i.e., in few milliseconds each) in the horizontal plane (i.e., HAC manoeuvres) when the clusters are made of 7 or less aircraft. As for clusters composed of 8 or more aircraft, the ICS is able to: identify those trajectories that are more tightly coupled within the clusters and then to propose flight level steps for those trajectories to solve the "tightly coupling" conflicts in a manner that "big" clusters are broken down into a set of clusters of a maximum of 7 aircraft.

Note that results obtained after several simulation experiments with different scenarios and assumptions indicate that the statistical frequency distribution of clusters shown in Fig. 5.1 is similar in all scenarios with comparable air traffic densities. This observation suggests that the cluster distributions presented in this research might be extrapolated to similar European air traffic scenarios in general.

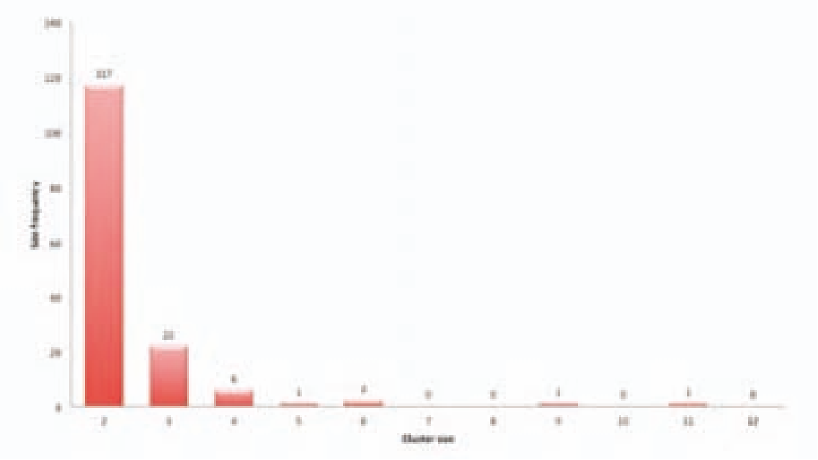

Figure 5.1: Cluster statistics for the nominal case (Dsep = 5NM). 211 conflicts.

5.3 Description of the CR Process

The CR process relies on two sub-modules, the RTG and the ICS. The RTG generates new resolution trajectories to solve the detected conflicts with a local optimization, –in this case– by means of an adapted GOA algorithm. By default, the original GOA algorithm introduces 2NM of buffer to the standard 5NM separation in order to provide with some looseness to the solutions for robustness purpposes [8, 56]. In this dissertation the same CR separation parametrization (i.e., 7NM) has been applied during RTG process in a first set of experiments. Additionally, in a second set of experiments the RTG has been set to provide resolution –horizontal– separation of 10NM between trajectories in conflict, which is an arbitrary value (twice the nominal safety separation) to illustrate the different effects in performance and robustness between the two CR parametrization versions (see Sections 5.4 and 5.5 below).

During the CR process, the RTG sub-module (set with the 7NM version) has generated an average of 3,57 trajectories per conflict, thus a total of 752 new trajectories have been generated, each of them calculated to solve at least one original conflict. Those trajectories have been then processed by the CD module (and stored in the SDS) that has predicted a total of 743 new interactions (i.e., secondary and tertiary conflicts).

A *best* solution was found by the ICS module, in this case according to a *min-*

imum total delay metric[1]. To obtain this conflict-free solution scenario, a total number of 193 trajectories were modified to solve all the 211 conflicts originally detected. Note that the difference in the number of trajectories moved with respect the number of conflicts solved is a consequence of the ICS algorithm that *naturally tends* to prioritize those scenarios that take most advantage from the positive/stabilizing domino effects.

Table 5.1 summarizes the main findings obtained after the CR process. Note that curiously the total amount of trajectories modified to obtain the best conflict-free solution is lower in the scenario in which a 10NM separation was forced between trajectories in conflict. It means that in this scenario the ICS algorithm could take better advantage of the positive domino effects, although the total cost of the solution is not necessarily lower.

Excellent results have been achieved for different sizes of clusters. Note that the 211 conflicts were distributed among 150 clusters (see Fig. 5.1) and that the 98% of the clusters did not involve more than 7 aircraft. For clusters of size equal or lower than 7 aircraft, the ICS can provide with several solutions (if any exists) sorted by a certain metric in a few milliseconds each, whereas solutions for clusters of size equal to 8 or 9 aircraft it could take up to 2 minutes (simulations for clusters with 10 or more aircraft were stopped after 2 hours since during the experiment such processing time was considered not valid for real-time purposes even if a CPU 10 times faster was considered). For run-time efficiency purposes, those clusters with more than 7 aircraft (which represent about the 2% of the total clusters) were re-clustered and reduced to several sub-clusters of maximum size of 7 aircraft (some resolution amendments applied to the residual 2% of the clusters consisted on generating new trial trajectories with the same nominal track but applying a +/- 1000ft FL change, which reduced the size of the clusters). After re-clusterization, the ICS has been able to succesfully provide with (near-optimal) conflict-free solutions for such 2% of the clusters in a timely manner.

Finally, once the CD&R algorithms provided with the best global conflict-free solution, all the new trajectories in such scenario that have been calculated by the CR (i.e., 193 in the 7NM scenario and 186 in the 10NM scenario, as seen in Table 5.1) have been "flown" with the Trajectory Predictor tool in order to check whether the amendments proposed by the CR are actually flyable. The obtained results indicate that all the trajectories proposed by the STREAM CD&R system have been flyable (BADA models applied for the simulation of the aircraft types under consideration).

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[1] This metric has been used as a simplification to obtain a *best* solution. Other metrics can be applied to find other *best* solutions, but the topic of metrics is not tackled in this dissertation (see Section 1.6 on page 49).

	7NM	10NM
Nominal trajectories	4010	4010
Resolution trials generated	752	723
Total trajectories after RTG	4762	4733
Nominal conflicts	211	211
2on and 3rd order conflicts	743	629
Total conflicts after RTG	954	842
HAC manoeuvres in solution	190	180
FL Changes in solution	3	6
Total modified trajectories	193	186

Table 5.1: Main results obtained during CR process with 7NM and 10NM

5.4 Performance Analysis of the CD&R System

Table 5.2 shows the contribution of each module to the total runtime of the application. Simulations have been run with a 2.6GHz 64-bit CPU, with a processor speed of about 650MIPS and equipped with 64 GB of RAM. For this nominal scenario, the CD&R algorithms presented in this dissertation have taken less than 80 seconds to obtain not one but several global solutions (solutions have been limited to a maximum of 10 per cluster, since for instance with the 150 clusters obtained in this scenario the total number of different conflict-free network solutions could be as high as 10^{150}).

Note that a faster CPU can reduce the total amount of time consumed by the algorithms in similar proportion/order of the CPU's MIPS increase applied. In addition, some processes such as the generation of resolution trajectories per each detected conflict (i.e., RTG sub-module) or the identification of solutions per each cluster (i.e., ICS sub-module) could be paralellized, thus considerably reducing the total run-time.

These overall results have shown an excellent computational performance of the design and implementation of the CD&R algorithms presented in this dissertation, thus suggesting that Strategic De-confliction under real-time restrictions could be supported by the proposed architecture.

Module	Runtime
CD	8 sec.
RTG+CD	41 sec.
Clustering	9 sec.
ICS	20 sec.
Total	**78 sec.**

Table 5.2: CD&R Simulation runtime

5.5 Analysis and Impact Assessment of the Uncertainty in the Nominal and the De-conflicted Scenarios

Different sets of experiments have been conducted in order to analyse and assess the impact of two different sources of the uncertainty in all the baseline nominal scenario and the Strategically De-conflicted scenarios (i.e., CD&R output). In addition, a robustness analysis of the CD&R proposed scenarios can be performed by comparing the number of conflicts effectively solved in the baseline nominally de-conflicted scenarios with respect the number of conflicts detected after applying different sets of perturbations to the baseline nominally de-conflicted scenarios (i.e., uncertain scenarios).

Note that these studies are mainly intended to demonstrate the capability of the strategic CD&R algorithms to perform such kind of analysis in further work, and therefore these results should be considered as preliminary. Also note that the results presented for this demonstration are just a small sample of what can be done in a thorough robustness analysis or a deeper assessment of the uncertainty impact in the proposed scenarios. Such comprehensive analyses could imply the generation and processing of hundreds or thousands of different scenarios (i.e., Monte-Carlo analysis) in order to obtain meaningful statistical results before deriving relevant and stable conclusions from them.

5.5.1 Robustness of the Nominal Scenario

Two scenarios with realistic Wind Prediction Errors introduced (scenarios WPE1 and WPE2) have been generated by BR&TE, and they have been considered together with two more scenarios generated by ALG-INDRA in which realistic Estimated Time of Departure uncertainties have been randomly applied to the flights, taking into consideration the typical delay distributions in Europe announced by EUROCONTROL (scenarios ETD1 and ETD2). More information about the methodology used to generate these scenarios can be found in STREAM Deliverable 4.2 [48]

Distance (CD)	**Nominal**	**WPE1**	**WPE2**	**ETD1**	**ETD2**
5NM	211	204	207	196	180
6NM	254	260	251	236	242
7NM	297	294	288	277	286
10NM	430	426	415	426	430

Table 5.3: Conflicts in different (non-deconflicted) scenarios

Another set of experiments has been also carried out in order to identify how the number and frequency distribution of conflicts change when extra strategic safety distances (i.e., buffers) are added to the minimum nominal safety distances used in the CD module to determine the presence of conflicts. Note that the introduction of safety buffers during the CD process might contribute to partially reduce the adverse effects of the WPE and ETD uncertainties at the moment of planning the ATM traffic with several hours in advance (i.e., strategic traffic planning).

Table 5.3 shows the number of conflicts detected in the nominal and the perturbed scenarios, organized by columns. Organized by rows, it is shown the number of conflicts that have been detected once an additional buffer (i.e., 1NM, 2NM or 5NM) has been added to the nominal 5NM safety distance and applied during the conflict detection in all the nominal and the perturbed scenarios.

For the scenarios with WPE uncertainties (i.e., WPE1 and WPE2), Table 5.3 (first row) and Figures 5.2 and 5.3 illustrate that neither the amount of conflicts nor the distribution of clusters have changed significantly when wind prediction errors have been introduced into the CD system.

For the scenarios with ETD uncertainties applied (i.e., ETD1 and ETD2), Table 5.3 shows that ETD uncertainties may paradoxically have (but not necessarily have) a stabilizing effect for the nominal scenario (i.e., reduction of the amount of conflicts from 211 to 196 and 180 respectively). In any case, what is important of these findings is that the presence of ETD uncertainties has noticeable effects in the robustness/stability of the traffic scenario, which suggests the importance of updating the NOP as soon as the ETD information of each flight becomes more precise. Note that as soon as the execution phase of the flights gets closer enough in time (e.g., 20 minutes before take-off), the ETD uncertainty is considerably reduced, thus allowing a more robust route allocation for that flight. In addition to the NOP rolling process, a probabilistic conflict detection process could be introduced in the strategic CD&R system in order to reduce the presence of false positive and false negative detected conflicts, thus contributing to improve

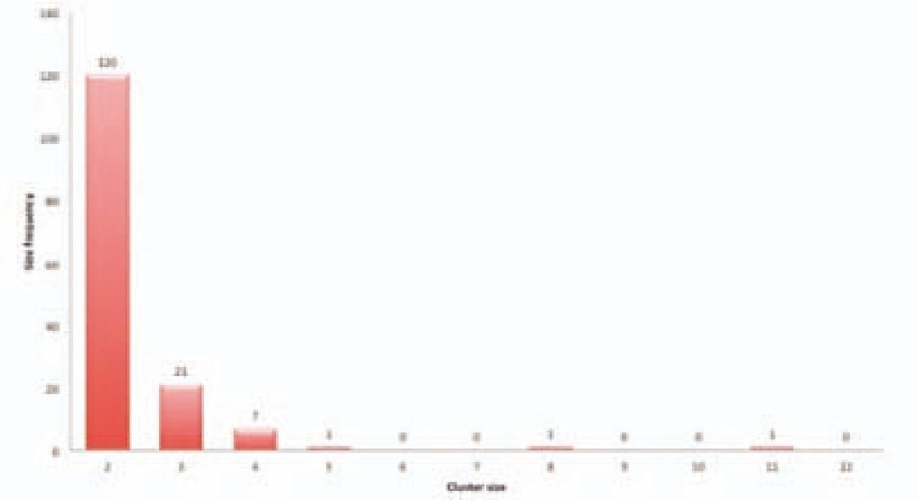

Figure 5.2: Cluster statistics for the nominal case with WPE uncertainties, case 1 (Dsep = 5NM). 204 conflicts.

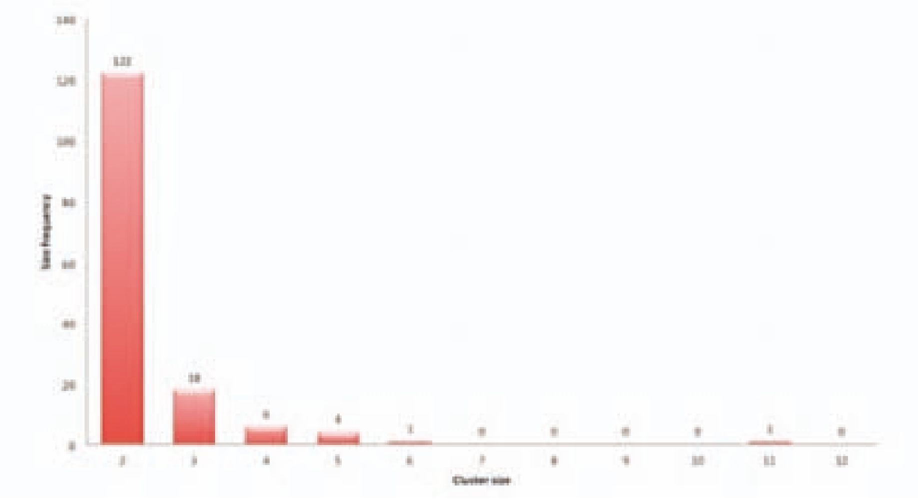

Figure 5.3: Cluster statistics for the nominal case with WPE uncertainties, case 2 (Dsep = 5NM). 207 conflcits.

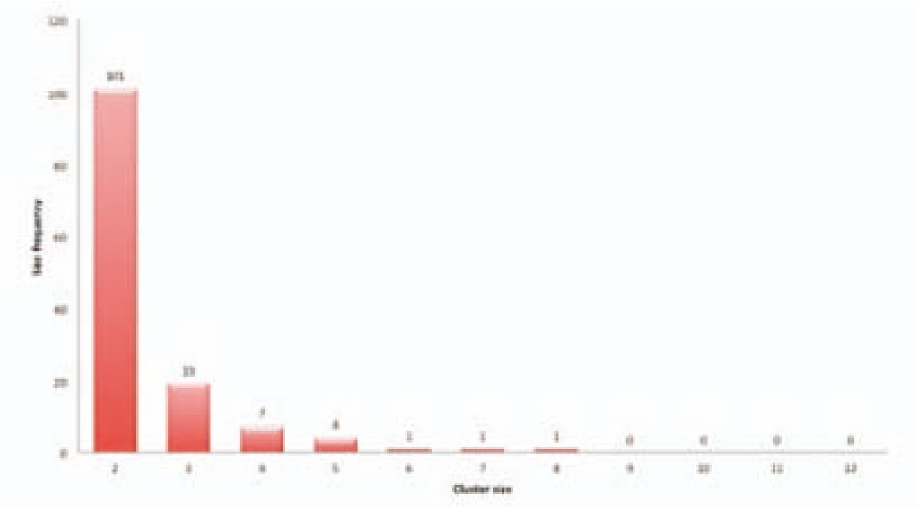

Figure 5.4: Cluster statistics for the nominal case with ETD uncertainties, case 1 (Dsep = 5NM). 196 conflcits.

the robustness and efficiency of the proposed CR amendments at strategic level. It is worthy to note that the distribution of clusters (Figures 5.4 and 5.5) is not significantly changed when the ETD uncertainties are introduced in the nominal scenario, which means that the introduction of these sources of uncertainty do not change the complexity of the scenario for the ICS module.

Figures 5.6, 5.7 and 5.8 show again that the frequency distribution of cluster-sizes does not significantly change in the different scenarios in which the size of the minimum required safety distance is increased. In all of the scenarios the 98% of clusters have been included in categories with 7 aircraft or less. Nevertheless, it must be pointed out that when the buffer is increased, the clusters tend to become bigger (note that in the extreme, and given a certain size of buffer, all the trajectories would be in conflict among them, thus belonging to the same unique cluster). Figure 5.8 (CD distance applied = 10NM) includes a maximum cluster-size of up to 21 aircraft.

Finally, after analysing Table 5.3 in more detail, it can be noted that there is a convergence in the number of detected conflicts among all the scenarios (nominal and perturbed) when the buffer is increased (i.e., the amount of conflicts is similar for all the columns/scenarios in the last row/10NM CD parameterization). The relative change among the scenarios (illustrated in Table 5.4) confirms such a convergence, and suggests that the robustness of the conflict-free solutions might be improved if a minimum safety distance of around 10NM (perhaps 11NM or

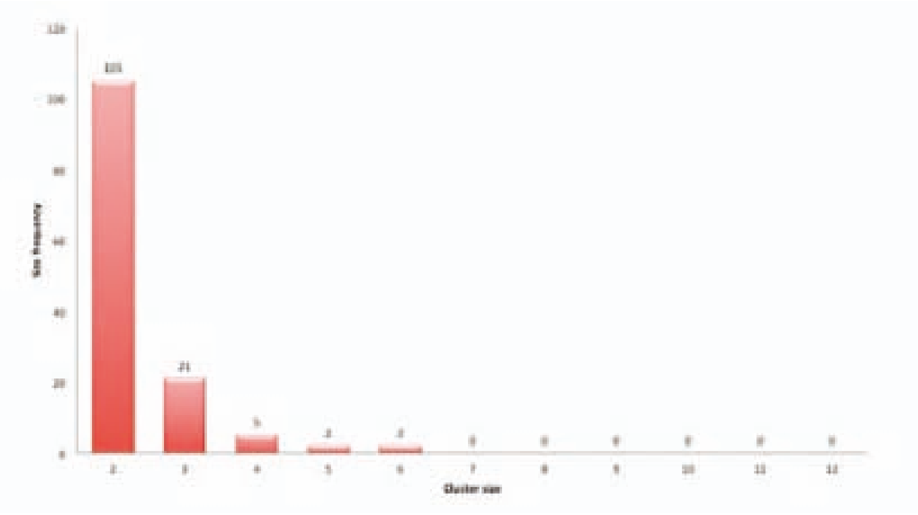

Figure 5.5: Cluster statistics for the nominal case with ETD uncertainties, case 2 (Dsep = 5NM). 180 conflcits.

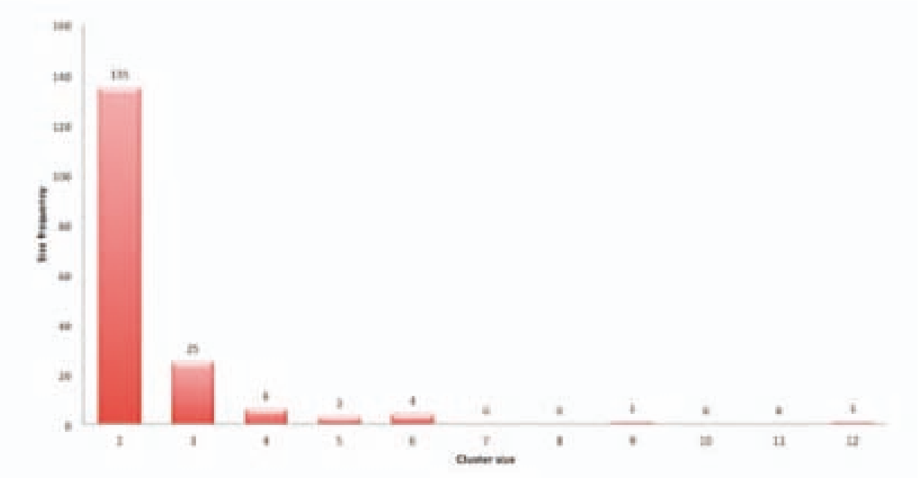

Figure 5.6: Cluster statistics for the nominal case (Dsep = 6NM). 254 conflcits.

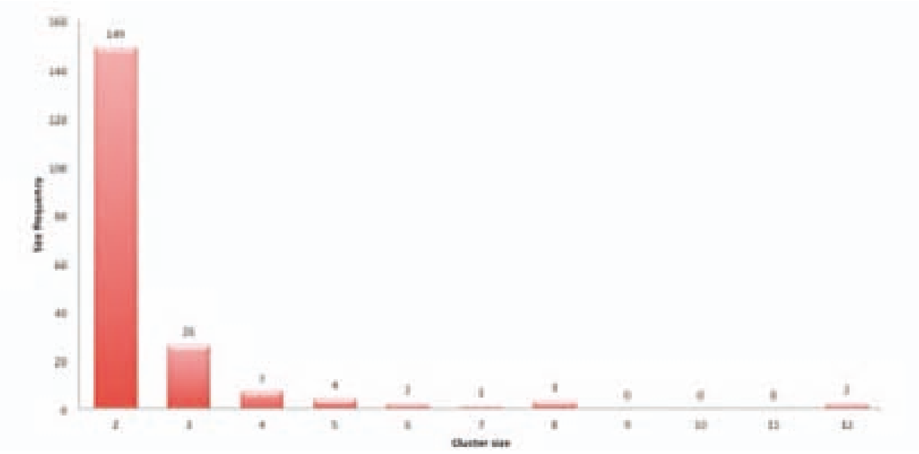

Figure 5.7: Cluster statistics for the nominal case (Dsep = 7NM). 297 conflcits.

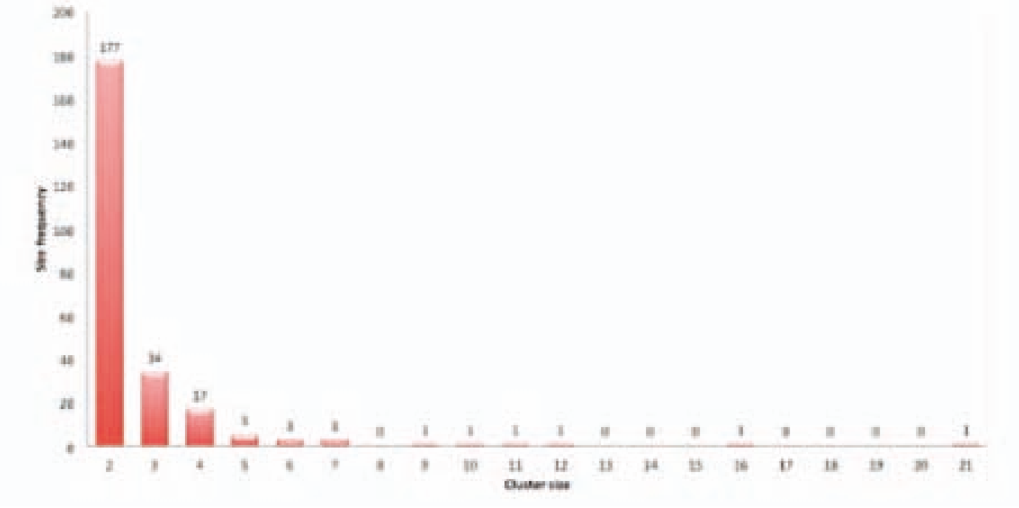

Figure 5.8: Cluster statistics for the nominal case (Dsep = 10NM). 430 conflcits.

Distance (CD)	Nominal	WPE1	WPE2	ETD1	ETD2
5NM	0.00%	-3.32%	-1.90%	-7.11%	-14.69%
6NM	0.00%	2.36%	-1.18%	-7.09%	-4.72%
7NM	0.00%	-1.01%	-3.03%	-6.73%	-3.70%
10NM	0.00%	-0.93%	-3.49%	-0.93%	0.00%

Table 5.4: Relative change in the number of detected conflicts with respect the nominal cases

Distance (CR)	Nominal	WPE1	WPE2	ETD1	ETD2
7NM	30	68	70	169	156
10NM	35	64	65	163	156

Table 5.5: Conflicts detected after processing the resolution trajectories with the Trajectory Predictor

12NM) is applied during the CD process (thus increasing the number of detected conflicts but ensuring that all the trajectories are separated at least 10NM in all their –nominal– 4D points after the CR process, a trajectory separation distance that seems to be robust to the presence of WPE and ETD uncertainties).

5.5.2 Robustness of the Strategically De-conflicted Scenario

After the CD&R process, one conflict-free solution has been obtained for each configuration of the RTG, i.e., 7NM and 10NM separations applied to trajectories in conflict. Each of the proposed resolution amendments (i.e., new flight routes) have been then processed by the Trajectory Predictor, thus obtaining realistic 4D trajectories that take into consideration the aircraft performance and aerodynamics. In order to evaluate a sensitivity analysis (for illustration purposes only), the CD module has processed these realistic trajectories generated by the TP in order to quantify how many conflicts have been effectively resolved by the CD&R system. The scenarios that have been tested include the nominal strategically de-conflicted scenario and also all the scenarios with perturbations, i.e., WPE1, WPE2, ETD1 and ETD2. Table 5.5 summarizes the results of this robustness analysis for all the considered scenarios. Table 5.6 shows information about the success rate of the CR.

A first point to remark is that after introducing the trajectories generated by the TP into the CD module, the nominal strategically de-conflicted scenario has resulted to be not conflict-free at all. This is mainly due to the CD&R and TP heterogeneities in the applied Earth models, i.e., the GOA algorithm that has been used to generate the resolution amendments has been adapted to con-

Distance (CR)	**Nominal**	**WPE1**	**WPE2**	**ETD1**	**ETD2**
7NM	85.78%	66.67%	66.18%	13.78%	13.33%
10NM	83.41%	68.63%	68.60%	16.84%	13.33%

Table 5.6: Success rate of CR (solved conflicts / nominal conflicts)

sider a spherical Earth model (i.e., aeronautical standard FAI sphere), whereas the TP employed to simulate the flights has used an ellipsoidal Earth model (i.e., WGS84). Since the differences between the spherical and ellipsoidal models affect the actual distances among the different geographical coordinates, some parametric errors have been actually introduced as a consequence in the results obtained. It must be also noted that introducing more separation in the resolutions (i.e., 10NM instead of 7NM) does not reduce the de-stabilizing effects of introducing different Earth models in the CD&R and TP systems.

Also note that both the 7NM and 10NM scenarios have been evenly sensitive to both sources of perturbation, i.e., the WPE and ETD uncertainties, therefore, increasing the CR buffer from 7NM to 10NM have actually not had any positive effect in the stability of the resolution scenarios.

Table 5.5 shows that WPE and ETD uncertainties have occasioned strong de-stabilizing effects in the scenarios amended by the CR (ETD uncertainties have generated greater de-synchronization effects). Paradoxically, Table 5.3 in the previous section shows that the WPE and ETD uncertainties have indeed had a stabilizing effect in the nominal non-deconflicted scenario, which can be observed in the actual reduction of the number of conflicts detected in the uncertain (non-deconflicted) scenarios with respect the nominal baseline (non-deconflicted) scenario.

Table 5.6 illustrates the degradation of the CR success rate for the different sources of uncertainty that have been applied to the 7NM and 10NM scenarios, thus confirming that the ETD-perturbed scenarios may seriously affect the robustness of the nominal conflict-free solutions (i.e., only a 13-16% of the predicted conflicts have been effectively solved by the CR strategic amendments). Such findings confirm the importance of relying on an dynamic rolling NOP in which the allocation of user-preferred trajectories can dynamically change in response to the updates of the ATM network state. Note that such dynamic rolling NOP could be supported by the CD&R algorithms presented in this dissertation. Additionally, the findings presented in Table 5.3 suggests that if trajectories are separated 10NM at each time-step, the additional buffer separation might allow to mitigate a large part of the de-synchronization effects of the WPE and ETD uncertainties. Thus, it is expected that by strategically separating the traffic trajectories in 10NM (perhaps 11-12NM) the conflict-free scenarios provided by the CD&R systems may be fairly robust in the presence of WPE and ETD uncertainties, i.e., scenarios strategically de-conflicted with a high CR success rate (not confirmed in this research, since the corresponding scenarios have not been flown with the TP of BR&TE).

Chapter 6

Conclusions, Main Contributions and Future Work

6.1 Summary of the Reseach

The foundation of the Single European Sky, and thus the adoption of the SESAR ATM concept, requires of new traffic management tools and procedures that can ensure the proper safety and efficiency levels for all the flights, while in turn enabling enough airspace/ATM capacity to support the future air transport demand expected.

This doctoral dissertation (which is fundamentally linked to SESAR WP-E STREAM project) has proposed the design and implementation of an innovative **CD&R system for strategic trajectory de-confliction** to be applied prior and/or during the flight execution of a **large number of 4D trajectories at wide regions of airspace**.

The strategic CD&R system has been successfully implemented (as a prototype proof-of-concept of the STREAM Strategic De-confliction concept) and has demonstrated the ability of supporting the storage and management of the entire 4D state space corresponding to the (simplified) European ATM system. The **main characteristics and contributions of the modules that compose the system** can be summarized as follows:

CD module:

- **Spatial Data Structures** have been used in the CD module as the vehicular technology to create a **micro-scale model framework of the ATM** in which it is possible to store and manage the entire set of 4D trajectories that shall be considered during the strategic planning of realistic European ATM scenarios (i.e., thousands of coexisting trajectories in a 2-hour look-ahead time).

- The use of a micro-scale model framework enables a **centralized and complete view of the state-space of the system** (i.e., the current state variables and its expected evolution along the time). Such a data framework is a key contribution since it provides with a global discrete event representation of the dynamic system, necessary for a **better understanding of the complexities and emerging dynamics** that cannot be understood without a global (4D/nD) perspective of the ATM system.
- The concept of **Relational SDS (RSDS)** has permitted considerably reducing the needs for computer main memory in more than 98%, which in turn has habilitated the **possibility to store and manage the 4D information of thousands of trajectories flying across the European airspace**.
- The concept of **Time-Space Data Structure (TSDS)** has allowed expanding the Near Neighbour Search to four dimensions (i.e., defining neighbourhoods as spatio-temporal regions), therefore such a pairwise spatio-temporal filter allows the comparison of thousands of trajectories (to detect potential conflicts among them) in a few seconds. **The computational runtime results obtained are excellent for real-time applications.**
- A **combination of the RSDS and TSDS technologies (i.e., RTSDS)** has been used to instantiate the ATM micro-model framework used in the Strategic De-confliction system**,** thus benefiting of the advantages offered by both techniques (i.e., little memory and runtime requirements).
- The RTSDS concept has been evolved to also take into consideration the **curvature of the Earth**, thus utilizing the **Geodesic SDS** concept (shown in the Appendixes) that is necessary to model a spatial region as wide as the European airspace.

CR module:

- The CR has been divided into two sub-modules in order to support the Strategic De-confliction requirements, i.e., the **Resolution Trajectory Generator module (RTG)** has been used to **provide local-optimal trajectories to individual conflicts** without having into consideration the rest of the traffic in the network (i.e., in an isolated way), while the **Interaction Causal Solver (ICS)** has been able to **explore the emergent dynamics** (i.e., domino-effect interactions) between the alternate resolution trajectories that are generated by the RTG (locally and isolated resolutions) with the rest of the trajectories in the network, thus being able **to find global optimal or near-optimal network solutions** (i.e., the *best* conflict-free route structures according to a set of agreed-upon metrics). The model is flexible to different objective functions commonly agreed to by the ATM stakeholders.

- A **Geometric Optimization Approach (GOA) algorithm adapted to the Strategic De-confliction requirements has been introduced into the RTG module as an approximation of the Airspace Users' preferences**, thus substituting the direct participation of the AUs by indirect methods, but without affecting the general validity of the CD&R system concept presented in this research (ideally, the Airspace Users should participate through direct or indirect methods in the calculation of these local-optimal trajectories, in a way such that the "optimality" of each flight is defined by the AUs according to their own business optimization logics).

- The analytical conflict resolution **formulae of the GOA algorithm have been adapted to take into consideration the curvature of the Earth** and to approximate geodesic trajectory resolution amendments, since they might be executed across a wide airspace of continental size. Some extra **adaptations have been also necessary for adapting the GOA algorithms to asynchronous traffic**, a traffic characteristic that can be found in strategic de-confliction scenarios (e.g., RBTs of airborne flights can be in conflict with SBTs of traffic already on ground).

- The excellent runtime performance of the RTG has allowed an **efficient integration between the CD and RTG modules, which is necessary to complete the ATM 4D picture stored in the SDS** with the information about the alternate trajectories that could potentially be assigned to the different flights of the scenario. Although the CD-RTG-CD cyclical process has been set in this research to a single iteration during the simulations conducted (a parameterization that has indeed resulted to be powerful enough to find fairly good near-optimal conflict-free solutions), the implemented CD&R system has left **enough room to support the parameterization of more CD-RTG-CD cycles**, which is expected to provide with more flexibility to find solutions to tertiary conflicts and to find more efficient solutions at network level.

- The causal model in this research has been **designed and implemented to reduce the size of the solution space to the Pareto-efficient frontier in which to explore and find feasible solutions** (the comprehensive analysis of the state-space cannot be afforded by current analytical or combinatorial methods since the strategic de-confliction with route multi-criteria optimization is a highly combinatorial problem that is considered to be untreatable, i.e., Non-deterministic Polynomial).

- The **ICS module has been able to take as input the qualitative information generated by the CD module** after the RTG process (i.e., interactions/conflicts among all the alternate trajectories that belong to different aircraft), a piece of information that can be extracted from the ATM micro-scale model stored in the RTSDS.
- The **ICS module allows the participation of the AUs in several steps of the Strategic De-confliction process** and includes their criteria in the calculation of the preferred solutions, i.e., facilitating Collaborative Flight Planning through dynamic route allocation at network level.
- The CR module has presented **excellent runtime performance** suitable for real-time environments.

6.2 Conclusions

The Strategic De-confliction system has been implemented in C++ with an Object Oriented approach. Several simulations of realistic scenarios have been performed and analysed to verify the correct functioning of the concepts. Simulation results have shown that this strategic CD&R tool is **excellent from the computational-efficiency point of view**, since it has been able of delivering a large set of conflict-free scenarios in less than 80 seconds provided a 650MIPS central process unit (CPU).

Several scenarios have been simulated to test the CD&R system, some of them introducing different assumptions and/or parameterizations, such as the use of loxodromic and orthodromic trajectories in distinct simulations, the application of spatial buffers of different sizes to separate the traffic in conflict (two different separation distances applied, i.e., 7NM and 10NM), and also the introduction of uncertainties in the traffic model, such as the presence of Wind Prediction Errors (which affect the precision of the 4D navigation) and the presence of uncertainty in the Expected Time of Departures (which also affects the longitudinal/temporal dimension of the trajectories). Results have showed that the application of **orthodromic trajectories have generated less number of conflicts than the loxodromic trajectories in the considered scenario** and that the conflict-free scenarios (calculated either with the 7NM or the 10NM parameterization versions of the CR) are **notably sensitive to the perturbations derived from the WPE and ETD uncertainties**.

All the **trajectories proposed by the CD&R system has been "flown" with a precise Trajectory Predictor** developed Boeing R&TE, thus confirming the flyability of the proposed de-conflicted scenarios.

Simulations with random WPE and ETD uncertainties applied to the traffic model (thus introducing errors in wind prediction and/or take-off times) **confirmed the importance of relying on a dynamic and continuously rolling NOP in which the allocation of the user-preferred trajectories can be dynamically changed in response to the updates of the ATM network state**. The CD&R algorithms developed for the STREAM project in this research have been designed for that purpose, and thus the SDS can update the complete 4D picture of the ATM every few seconds. The RTG and ICS algorithms can also provide with several near-optimal conflict-free solutions in a few seconds or minutes if a medium-powered computer is used. An update frequency of around 2 minutes for the NOP could actually contribute to manage the uncertainty by updating the state of the ATM as soon as the relevant information becomes more precise (e.g., the ETD of a flight).

If the safety distance is increased with the application of a buffer during the CD process (e.g., declaring a conflict when 2 aircraft are in the horizontal plane at less distance than 10NM instead of the nominal 5NM) could improve the robustness of the de-conflicted scenarios. As seen in the simulation results, increasing the CD buffer entails more conflicts (around 43 conflicts per extra NM buffer in the considered scenarios) which implies higher costs related to the additional resolution amendements required; however, **the achievement of more robust and predictable scenarios might compensate the cost of the additional resolution amendments**.

Finally, the preliminary results obtained indicate that **the proposed CD&R system could contribute to developing a subset of the aspects required for Strategic De-confliction during real-time Collaborative Flight Planning in the presence of large number of trajectories**, thus representing a baseline for more advanced and realistic solutions and an evolution towards the full ATM automation.

6.3 Main Contributions

With regards to the objectives stated for this research (which in turn are tightly related to the objectives of the SESAR programme), the following main contributions of the CD&R algorithms developed have been identified:

Safety: It is expected that the anticipation of the aircraft separation tasks through strategic de-confliction for the entire duration of all the flights may contribute to maintain or outperform the current safety levels in the ATM while still leaving room for the optimization of routes and to support an increase of the airspace demand. Note that the strategic de-confliction system proposed in this research is compatible with the others layers of safety provided by the current tactical surveillance and management of conflicts of ATC as well as with the on-board collision avoidance systems (i.e., TCAS). Also note that the simulation results have showed that the addition of buffers to the nominal safety distances could contribute to generate conflict-free scenarios that are robust to most typical sources of uncertainty, i.e., navigation uncertainties due to wind prediction errors and take-off delays (i.e., WPE and ETD uncertainties), thus actually reducing the probability of conflicts (and mid-air collisions) in the ATM network.

Capacity: The system has shown the ability of efficiently performing strategic de-confliction among thousands of 4D trajectories, thus finding new conflict-free flight plans (through a dynamic route allocation process) in a few seconds (less than 90 with a medium-power 650MIPS computer). The potential reduction of the ATC's workload may contribute to reduce the latent capacities present in the current ATM system, while the elimination of fixed route structures may contribute to take better advantage of the available capacity during the flight planning process.

Flight efficiency, ATM cost-efficiency and environmental impact: According to a certain agreed-upon definition of trajectory optimality for each flight, the system is able to find optimal or near-optimal global network solutions. The system allows the introduction of the Free-Route concept (simplified as Direct Route in this document), which may contribute to save fuel and time as well as to reduce pollution in the ATM. In addition, the consideration of the emergent dynamics and potential interactions among the different 4D trajectories allows the CD&R system to find those feasible network solutions that are closest to the AUs preferences taking into account a global perspective. Note that the CD&R system is compatible with other strategies applied by the NM to manage the ATM direct costs per flight and to reduce the environmental impact of flights, such as the application of different taxations to flights according to the sectors crossed or the estimated pollution generated (i.e., the concept of Free-Route allows the Airspace Users defining their prefered trajectories, thus all their proposed trajectories already internalize the different ATM direct-costs and restrictions).

SESAR conformance: The CD&R developed for STREAM project relies on the same future technologies that will give support to the SESAR ATM concept, such as the deployment of the 4D-FMS navigation, the data-link communications, and the new aircraft-dependent surveillance systems, together with the SWIM platform to share and synchronize the entire ATM information. The use of 4D trajectories, the CDM philosophy, the unification of different airspaces into a single one, the flight and network efficiency, the equity and fairness considerations and the flexible dynamic route allocation are all concepts that match with the SESAR strategic interests:

- **Use of 4D trajectories**: The CD&R system presented is able to process and store the complete 4D description of all the alternate trajectories (either in SBT or RBT format) associated to all the flights present in a certain scenario under consideration. The sampling rate of the trajectories has been parameterized to one sample per second, which is a fairly high resolution taking into account the dimensions and speeds of the commercial aircraft. Other parameterizations are also possible (e.g., a sample for each 10 seconds).
- **CDM philosophy**: The system allows the participation of AUs in various levels of the CD&R process taking into account their local and global preferences in order to deliver the solutions with transparency.
- **Global scope**: The entire European airspace is examined simultaneously as a single sector, thus avoiding any border problems within the current sectors of the European ATM. In addition, a global scope may contribute to obtain more efficient solutions since the emergent dynamics derived from local decisions of the system can be analysed with a network perspective, thus providing with global solutions that *naturally tend* to prioritize those scenarios that take most advantage of the positive/stabilizing domino effects (i.e., less trajectories are modified with respect the number of conflicts detected in the baseline non-deconflicted scenario). Note that the presented system is still compatible with the NM restrictions potentially applied to regulate the traffic at the level of flows as well as to limit the number of aircraft crossing a certain ATC sector.
- **Equity and Fairness**: The potential assessment of several conflict-free Pareto-efficient scenarios to evaluate their impact on the ATM stakeholders may be a key factor to ensure equity and fairness among all the AUs (considered but not evaluated in this dissertation).
- **Flexibility**: In SESAR, flexibility is the ability to adapt the ATM planning to unexpected network changes. The fast updating rate of the (4D/nD) ATM state-space micro-scale model together with the CD&R algorithms presented in this dissertation can be a contributor to support strategic deconfliction in real-time applications, which in turn could be useful to enable

the necessary real-time negotiations of the NOP (through a dynamic route allocation process negotiated among all the stakeholders), and it may also contribute to deal with some sources of uncertainties that often cause unexpected changes in the network (e.g., delays, weather, wind prediction errors, trajectory deviations, and so on).

6.4 Future Work

The following list is a summary of interesting ways forward in the development of the CD&R algorithms presented in this research:

1. Technological enabler for the Integrated Network Management and extended ATC Planning Function (INAP)

Recently, the SESAR ConOps Step 2 [47] has introduced a new planning layer called INAP (or Integrated Network Management and extended ATC Planning Function), which aims at **coordinating the ATFCM decisions made regarding the network flows with the ATC decisions made regarding the individual flight trajectories at local sectors**. The underlying concepts of this layer are similar to the ones researched under the STREAM project, and thus the strategic de-confliction algorithms presented in this dissertation could actually contribute to the materialization of this new traffic planning layer of SESAR ATM.

2. Improvement of the RTG module

The RTG module presented in this dissertation has been based on a GOA algorithm adapted for Strategic De-confliction and has been used as a simplification method to obtain the "user-preferred" trajectories generated to avoid the conflicts detected. Note that for researching purposes in general, and for this research in particular, such abstraction has been found to be fairly appropriate. However, in the current CD&R system implementation only heading change manoeuvres have been implemented as a general resolution method to solve conflicts (note that flight level changes have been also applied in a few some cases, but not as a general method for all the conflicts). Therefore, although the results obtained have been actually excellent, it is still recognized that the **implementation of more resolution manoeuvres** (such as flight level changes, speed control, and the imposition of controlled times at certain points of the route) may contribute to obtain more efficient and robust scenarios.

3. Improvement of the ICS module

As stated in the limitations identified for this research in Article 5, there are several ways to improve the current ICS module. For instance, **the number of CD-RTG-CD cycles could be increased** and thus parameterized to several cycles (currently it is parameterized to one single cycle). So, the ICS could use the information about the additional secondary and tertiary conflicts, thus having into account a more complete set of local-optimal trajectories, which increases the probability of finding conflict-free solutions in a given scenario (specially among tightly coupled trajectories) and also gives more flexibility to optimize the conflict-free scenarios. **New strategies to re-cluster** can also bring new insight to the light about the complex interactions that sometimes can occur among diverse trajectories.

4. Multi-criteria cost-benefit analysis

Only the metric of *minimum delay* has been considered online during the ICS process to (simplistically) determine the optimality of the conflict-free scenarios to be provided by the system. Under the STREAM project several metrics have been defined (efficiency, robustness, equity, fairness, among others) in order to analyse and evaluate the performance of the solutions delivered by the CD&R tool presented in this dissertation. Therefore, these metrics could be actually implemented in the current CD&R system in order to improve the automated decision-making through the **online evaluation of a multi-criteria cost-benefit analysis**. The introduction of more sophisticated metrics that can be considered online shall contribute to define a set of Pareto-optimal conflict-free scenarios and the posterior evaluation in order to decide which one of the feasible scenarios is the most preferred one and thus to proceed with the plan execution.

5. Use of a more realistic n-dimensional ATM model

The prototype version of the strategic CD&R algorithms presented in this dissertation only have considered simple strategies to tackle uncertainties (e.g., increasing the minimum safety distances with buffers in both the CD and the CR modules). Nevertheless, the CD&R algorithms of this dissertation have been designed with the perspective of a potential future version upgrade that integrates **additional state-space variables to model a more realistic n-dimensional ATM** (e.g. including probability values to model different ATM aspects, such as the risk-of-deviation of the trajectories or the severe weather occurrance in a given sector or airport) during the CD&R processing in order to take better decisions with an overall consideration of the network. This approach could potentially help to the ATM stakeholders in relation with the different SESAR Validation Activities for real-life applications in which more state variables must be considered.

The introduction of a probabilistic conflict detection (e.g., based on known probabilistic distributions that allow describing both the *Wind Prediction Errors* and *Estimated Time of Departure* uncertainties) could help to generate more stable/robust route allocation plans. Thus, the resolution amendments that are proposed in the current CD&R version could be reduced or adapted in the presence of conflicts identified as “improbable”. In addition, note that such probabilistic conflict detection (and resolution) might be strongly benefited from the fast network re-planning frequency achieved in this research (that allows de-conflicting all the trajectories in less than 2 minutes), since the conflict probabilities associated to uncertain events (such as conflicts) are expected to change and become more precise as soon as the time of execution becomes closer.

6. Temporal looseness computation to tackle some sources of flight uncertainty

The *speed uncertainties* derived from the wind prediction errors and the *ETD uncertainty* derived from a typical European delay distribution have been the main flight uncertainties considered in the framework of STREAM project (see Section 3.3 and Appendix A.5). As seen in this dissertation, the negative desynchronization effects of these uncertainties can be mitigated at certain extent with the use of additional buffers applied to the minimum safety distances required among aircraft. Note, however, that these uncertainties affect to the temporal/longitudinal dimension of the trajectories, thus it seems more appropriate and more precise to tackle these uncertainties in the temporal dimension and not in the spatial domain. The concepts shown in Article 3 and in the AppendixA.5 about uncertainty with regards to the calculation and management of the temporal looseness of the trajectories can bring to light **new insight and new strategies to tackle those uncertainties that affect the temporal dimension** of the trajectories.

Similar configuration of the SDS showed in Article 1 (see on page 131) that can be applied to detect wake vortex encounters can be also applied to compute the temporal looseness of the trajectories, i.e., how many units of time can a trajectory be delayed or advanced without generating a new interaction in the network. This information may be useful as a strategy to tackle some sources of uncertainties (such as speed and ETD uncertainties) and also could be useful to **identify more robust conflict-free scenarios** (e.g., less efficient loose/robust scenarios could be preferred over more efficient but tightly coupled scenarios). Also the information about the loosness of a flight could be useful for ATCOs in case the traffic at their local sector level need a re-planning, since **by identifying the less tightly coupled trajectories ATCOs could minimize the potential negative impact of their decisions in the downstream sectors.**

7. Consider TP uncertainty at strategic level

An important new concept has been introduced in the Appendix A.5 of this dissertation with regard to the possibility of planning the 4D trajectories of all flights at strategic level whereas **taking into account what the tactical controllers will see at each ATC sector during the execution phase.** Specifically, the risk-of-deviation (considered here as part of the TP uncertainty) that is currently only computed during the tactical conflict management should be also considered at the strategic de-confliction phase (enough TP precision is assumed as in the SESAR context). The risk-of-deviation can increase the workload of the ATCOs during flight execution phase, since the strategic traffic plans will be modified at the tactical phase if the ATCOs observe a situation that, even when the nominal trajectories may be conflict-free, the risk of collision computed through the TP risk-of-deviation model is considered too high (thus usually getting less efficient and more unstable traffic plans than the planned at strategic planning level). Therefore it is proposed as a further work to extent the CD&R algorithms with a risk-of-deviation model applied not only at tactical level, but also during the strategic de-confliction process.

8. Simulation of a dynamic NOP with eventual/stochastic Network disruptions

Simulations presented in this dissertation have only considered one strategic CD&R run per scenario. However the system has been designed to update the state-space in few seconds or minutes, in order to respond in a flexible way to the changing ATM conditions. Thus, it is proposed as a further work the implementation of a complementary simulation platform that generates random network perturbations (such as severe weather, trajectory deviations, the sudden closure of sectors and/or runways, and so on) that obligates to reconsider the original nominal planning and to generate a new one during the execution phase in a **continuous rolling CD&R process.**

This would provide a more realistic environment in which the simulation of a dynamic NOP can feed and update the strategic CD&R system every 2 minutes and the conflicts are defined probabilistically according to some reasonable/realistic statistical distributions which in turn can be weighed up according to the look-ahead time of the predicted conflict compared with the updated current-time of simulation. Relevant insight about the ATM can be obtained with the results provided by the CD&R system, thus contributing to develop new strategies to mitigate the adverse effects of several sources of uncertainty and to design more robust strategically de-conflicted scenarios.

9. Extensions of the technological framework for the deployment of real-time applications

Note that updating the CD&R system with improvements in the technological framework, such **a faster runtime performance, may contribute to support larger amount of trajectories and conflicts in a timely manner** for real-time purposes. It also may contribute to **compensate the potentially large information transmission lead-times in case of real-life applications** in which the aircraft must send/receive the trajectory information to/from the NOP. Therefore, extra opportunities to improve the execution performance have been identified, for instance, a faster CPU can be used (the used 650MIPS processor is indeed a relatively slow CPU compared to nowadays computational capabilities) and/or some of the algorithmic processes can be parallelized, especially the generation of local resolution trajectories per identified conflict (i.e., each conflict can be processed in parallel in the RTG module), and the causal analysis after the identification of conflict clusters (i.e., each cluster can be processed in parallel in the ICS module). Additionally, the causal analysis of big clusters (i.e., size of more than 7 or 8 aircraft) can also be benefited of parallel computing, since many of the internal operations of the ICS module causal exploration can also be run in different processors. In this manner the amount of time required to reach an optimal solution for a big cluster could be drastically reduced, thus increasing the maximum cluster size supported without needing of re-clustering (better solutions may be found if re-clustering is avoided).

10. Integrate the Strategic De-confliction system with the MTCD for TMA as a first step for airport integration

According to new SESAR ATM concepts, the planned take-off time of a flight will be conditioned (through backtracking the trajectory) to the target time of arrival negotiated between the airlines and the airports and agreed by the NM. However, once the aircraft will be airborne, and due to the negative effects generated by the presence of uncertainties and perturbations, it is expected that some degree of traffic de-synchronization will be present, which could be partly alleviated in the en-route phase by a continous rolling strategic de-confliction system like the one presented in this dissertation.

However, the **trajectories arriving to TMAs that are still de-synchronized at the begining or during the approach phase may require the integration of the en-route strategic de-confliction system with a tactical MTCD system** (like the one presented in Article 1), which in turn shall work together with an AMAN/DMAN system in order to schedule/re-schedule the approaching traffic with the purpose to optimize the runway utilization, specially during high-complexity operations [77, 79] (and ideally also minimizing the changes on the take-off schedule, in case the runway is configured in mixed mode, in order to avoid/minimize the reactionary de-synchronization effects at other sectors).

Hence, once the AMAN/DMAN has calculated the optimal landing sequence for the traffic that is approaching to the airport and that is in the working horizon (e.g., 30-40 minutes look-ahead), the MTCD can start a dynamic route allocation process in which the actual airport and sector restrictions are taken into account together with the aircraft performance and the user preferences through a collaborative decision making approach. At the end of this negotiated tactical deconfliction process, a set of 3D waypoints and time-restrictions (i.e., CTAs) shall be calculated online with precision (i.e., waypoints not previously published) in order to generate a set of conflict-free trajectories that will be assigned to each corresponding flight and cleared during the approximation, descent and landing phases. Note that this strategic and tactical integration at TMAs could constitute an important step towards the airport integration targets pursued by SESAR.

11. Complete airport integration

The full airport integration in the ATM concept is perhaps the most ambitious target of SESAR since it implies the integration of the airside planning with the complex logistics of all the airports in the network [32] (including taxiing, turn-around, flight services at airport, handling and boarding processes among others), and thus also requiring to take into account the schedule of the airlines for different flights that may be served with the same aircraft and same or different crews.

After the integration of the MTCD for TMAs (explained in previous point), the next natural step should be the complete integration of airports, thus the CD&R system presented in this dissertation could be useful to perform studies in which to **observe how decisions made in the airports at local level may propagate across the network**, thus affecting the robustness of the trajectory planning as well as the potential complex reactionary effects indirectly caused by local decisions at a given airport over the same airport, e.g. decisions made to optimize the performance of airport A for a certain look-ahead time could obligate to change the optimal local decisions made in airport B, which in turn could affect again (directly or indirectly) to the optimal decisions in airport A, thus questioning if the first decisions in airport A were actually optimal.

12. Extension of the technological framework to other ATM research programmes

This research has been developed taking into consideration the SESAR ATM concepts and objectives. Nevertheless, the same technological framework could be adapted and applied to other similar ATM research programmes such as NextGen in USA or CARATS in Japan, among others. It could additionally contribute to the **potential coordination of the traffic planning between the European ATM and other ATM research programmes** (see for instance the Forum for the Integration and Harmonization of NextGen and SESAR into the Global ATM Framework [http://legacy.icao.int/inexses]).

13. Wake vortex encounters avoidance in the en-route airspace

Wake vortex phenomena [15] has been traditionally considered only during TMA operations [9, 109]. The current en-route safety procedures have traditionally been conservative enough and thus any potential risk of a severe wake vortex encounter during en-route operations is currently considered insignificant. However, new ATM concepts can be introduced in the future and thus it could be necessary to also **consider the potential severe wake vortex encounters in the en-route airspace** [72, 54, 82]; for instance with the introduction of the Free-Route/Free-flight operations, with the potential elimination of the flight levels layers to improve vertical flight efficiency, and/or with the forecasted changes in the aircraft mix of the future air transport (i.e., bigger aircraft together with smaller aircraft with respect current aircraft mix) and the augment of traffic densities. A MTCD&R system has been presented in Article 1 that can use simplified wake vortex models for the determination of conflicts based on a given set of time-based separations. Some adaptations could be applied to the SDS used in such MTCD system in order to adapt the same concepts to the entire European en-route airspace, thus integrating spatial-based and time-based separations during the strategic de-confliction process, which adds a new layer of safety to the ATM.

14. Complexity maps

As argued along the pages of this dissertation, the SDS concept (and its variations) admits the storage of n-dimensional information. Therefore, this characteristic of the SDS technology could be used to **generate complexity maps during the strategic de-confliction process** [67]. Such maps could contribute to provide the CD&R system with improved information about the network and flows states, thus enhancing the decisions made through the consideration of complexity metrics that shall warn about potential traffic situations in which the risk of incidents/accidents could be considered too-high from the safety point the view even when the nominal 4D trajectories may be conflict-free (e.g., a sector pre-declared capacity overload).

15. Identification of hot-spot areas

The highly-efficient computational performance achieved by the CD system and the State-Space data framework enabled by the SDS (or the RTSDS) could be useful for the integration of DSTs designed for the ATFCM control of flows in the real-time. Of particular interest (according to some EUROCONTROL experts) could be the **real-time identification of geographical areas that may have high probabilities of becoming unstable** (i.e., hot-spots), for instance due to a high number of conflicts predicted to occur in a same spatio-temporal region. The analysis could be complemented with the consideration of complexity maps (previous point of this future-works list), with a probabilistic analysis of the hot spots derived from the consideration of TP uncertainties at strategic level (point 7 of this list) and also from the consideration of probabilistic RBTs in the presence of uncertain events that may affect the network capacity (point 19 of this list). A major degree of realism and more trustful results could be obtained during the identification of hot spots if the simulations are run as a dynamic rolling process in which stochastic network perturbations are systematically introduced (point 8 of this list). Therefore, such analytical tool could contribute to a more precise and robust ATFCM management of capacities and flows in a Trajectory Based Operations environment.

16. Add weather information

Similarly to complexity maps, **the SDS could also store different weather parameters information**, thus being able to generate wind 4D maps, temperature 4D maps, and so on. This information can be used by the CD&R to make better decisions with regards to the efficiency of the flights and the robustness of the scenarios.

17. Impact assessment models

The availability of the discrete event ATM representation supported by the SDS technology, together with the possibility to integrate causal models that explore the state space of the system (to anticipate the propagation of the local decisions and their collateral effects across the network), could be used to develop **models that assess the impact of those local decisions**. Such impact assessment models shall allow improving the decision-making processes or to perform offline studies of past scenarios in order to assess the effectiveness of the decisions previously made.

18. Test-bed Platform for ATM Studies (TPAS)

The CD&R algorithms that have been presented here (and which are supported by the modelling data framework provided by the SDS technology) are currently being re-coded in format of a distributable DLL to facilitate the interaction to third party users through the usage of a set of properly documented API functionalities. The idea is to offer to the scientific community a simulation platform with several tools that are integrated in a single modelling framework in order to facilitate the fast prototyping of new ATM concepts and the test of new Decision Support Tools.

Therefore, the Test-bed Platform for ATM Studies (TPAS) has been **designed to provide a computer-based test bed environment for the development and evaluation of new ATM tools as well as the verification of new ATM concepts** that may contribute to a better understanding of the ATM system. TPAS can efficiently manage, represent and store ATM information of micro-level objects (such as 4D trajectories either in SBT or RBT format, airspace data

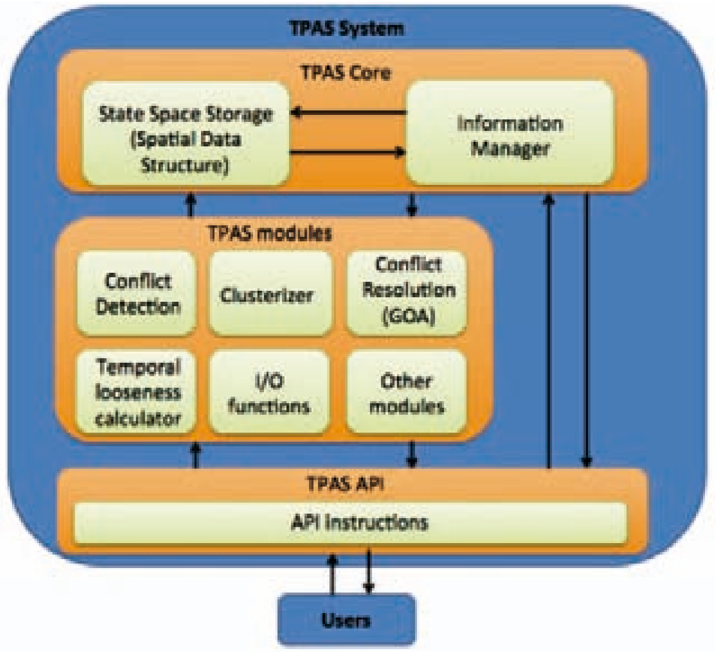

Figure 6.1: TPAS system architecture

The Test-bed Platform for ATM Studies consist on a kernel that includes a SDS and the Information Management module together with different functionalities that could be useful for researchers and ATM users to generate insight about the ATM and also to ease the design, implementation and testing of new Desision Support Tools and ATM concepts.

and weather information) with a global and n-dimensional view (thus potentially extending the simplified 4D ATM model assumed in this dissertation). This can represent a key contribution for ATM researchers and users since this framework shall enable the observation and management of the potential emergent dynamics appeared in the network as a consequence of the decision-making processes that are based on a narrowed local-level perspective.

The system architecture that has been developed for TPAS is illustrated in Fig. 6.1. The following modules will compose the kernel of TPAS:

- *State-Space storage and management (Spatial Data Structure)*
  The State-Space storage and management module is in charge of enabling a micro-model discrete event representation of the ATM as well as in charge of providing efficient access methods (reading/writing) to such state-space information. This module is enabled by the use of a database with special design and implementation requirements, i.e. Spatial Data Structure (SDS),

which is detailed in Articles 1 and 2 (on pages 131 and 155respectively) .

- *Information Manager*
  The Information Manager (IM) is in charge of an efficient management of Aircraft, Routes, Trajectories, and any other ATM information required in the models under consideration. Specifically, this module is in charge of the:
  o Management of aircraft information (e.g. flight number, aircraft model, mass. . .)
  o Management of original trajectories/flight plans o Management of alternative/trial trajectories/flight plans (e.g. proposed by a CR system)
  o Generate trajectories from routes/flight plans (through simple or advanced TPs)
  o Add ATM information to the SDS (e.g. 4D trajectories) o Delete ATM information from the SDS (e.g. 4D trajectories)
  o Extract ATM post-processed SS information from SDS (e.g. conflicts, temporal looseness, complexity map. . .)
  o Management and classification of ATM SS information (e.g. temporal sorting of conflicts, computation of basic metrics, statistics. . .)
  o Coordination of the functionalities of all the modules

Aircraft may have more than one potential trajectory, yet because of the consideration of uncertainty (i.e., probabilistic trajectories), yet because the consideration of alternate trajectories generated during a trial and error flight planning optimization. Therefore, the IM and other TPAS modules (e.g. the CD, CR. . .) require a method of identification for the trajectories that are associated to the same aircraft. TPAS provides the users with efficient automated methods for such trajectory identification (see Appendixes of this dissertation).

To aid the ATM stakeholders with the creation and verification of new ATM concepts and DSTs, the TPAS system has been designed with a modular approach that supports the integration of external tools, through the use of a set of APIs that include several primitive functionalities (e.g. create and parameterize aircraft, create route/flight plan and assign it to an aircraft, generate a 4DT from a route/flight plan, load a 4DT from a file and assign it to an aircraft, compute geodesic or loxodromic distances between waypoints, etc.) and different tools and functionalities that are already integrated and distributed with TPAS that shall be helpful to perform several kinds of ATM studies (i.e., conflict detection tool, clusterizer tool, temporal looseness calculator, strategic de-confliction and more). Also some realistic network-level scenarios for test-bed purposes will be included, thus providing a common modelling framework to test different external Decision Support Tools and new ATM concepts and thus enabling performance comparison among different approaches applied to the study of a certain same ATM concept.

TPAS has been programmed in C++ and it is multiplatform (i.e., it can be run under Windows, Mac, Unix, etc.). It supports 32bit and 64bit CPU architectures, and thus it can be configured to manage large amount of data stored (for efficiency purposes) in main/RAM memory.

19. New SBTs/RBTs management tool under the presence of uncertainties

The concept of RBT is used in SESAR as the optimal reference trajectory that considers the airspace user preferences and the network restrictions from the origin airport up to the destination airport. In this dissertation is proposed, as part of a future work, to extent this concept with the introduction of probabilistic trajectories (or perhaps probabilistic trajectory segments).

Note that the information about the probability of occurrence of a certain event (e.g., a severe thunderstorm) is more precise the closer is the prediction with respect the potential time of occurrence of the event. Thus, **different probabilistic trajectories should be considered in those cases in which a certain event could happen with a certain probability and may affect the normal execution of a nominal RBT**. Therefore, the definition of "optimal RBT" shall be reconsidered with regards to such probabilistic information of the event. For instance, see Fig. 6.2 in which a particular flight is taking off at time t0 and a certain event (i.e., a severe thunderstorm) is predicted (at time t0) to likely happen with a probability p=0.5 at time t0+60'. Let us consider that due to the nature of the event, the prediction/probability of the event will be perfectly known 30 minutes before the event, thus in t0+30' it will be perfectly known if the event will actually happen (p=1) or not (p=0). If the event would not happen, the preferred trajectory for that flight would be trajectory *a* in the figure, whereas if the event would finally happen the preferred trajectory would be trajectory *d*. Thus, the optimal decision in t0 with the information available should be to fly to an intermediate point at t0+30' (ideally calculated taking into account the optimization logic of the Airspace User for that flight and weighing up the probabilistic information about the occurrence of the uncertain event) thus flying the first segment of trajectories *c* and *d*. In time t0+30', when the information about the actual occurrence of the event will become more precise, the rest of the RBT segment will be decided, which could be the segments of trajectory *c* (in case that p=1 at t0+30') or trajectory *b* (if p=0 at t0+30').

Note that (in this case) at t0 both trajectories *b* and *c* have the same probability of finally being flown, thus both trajectories should be considered as probabilistic RBTs and the potential interactions of these trajectories with other flights should be weighed up with their respective probability values associated. The CD&R platform presented in this dissertation can be adapted to support this

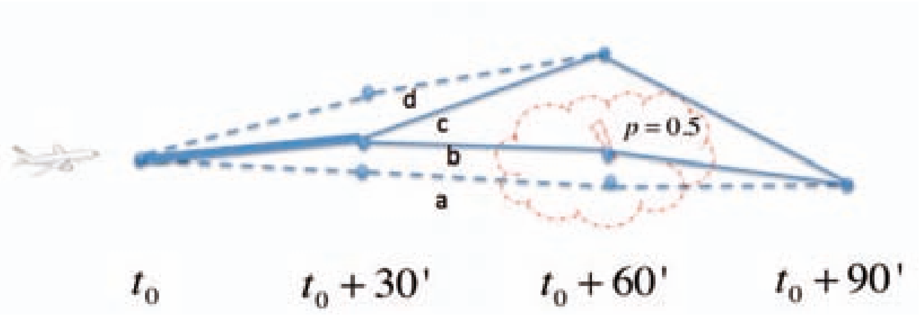

Figure 6.2: Probabilistic SBTs/RBTs to tackle some sources of ATM uncertainty

The ATM conditions and constraints may dynamically change due to the presence of uncertain events in the network, thus potentially affecting the decisions made several minutes or hours in advance with regards to the 4D trajectory intentions. Thus, airspace users might want to consider different alternate plans for their 4D trajectories calculated with probability values associated as a potential response to the uncertain/probabilistic events of the network.

kind of probabilistic models in which the probabilistic information of the trajectories can be stored as extra n-dimensional information in the SDS. Also note that the high updating rate of the SDS content and of the strategic de-confliction process is a key factor to take better decisions as soon as the probabilistic information associated to certain ATM events becomes more precise with the pass of the time.

Chapter 7

Compendium of Published Articles

7.1 “*A Medium Term Conflict Detection and Resolution system for Terminal Manoeuvring Area based on Spatial Data Structures and 4D Trajectories*”

Article 1, “*A Medium Term Conflict Detection and Resolution system for Terminal Manoeuvring Area based on Spatial Data Structures and 4D Trajectories*”, has been published in the journal of Elsevier Transportation Research part C. The content of this paper is presented as the seed of the technological framework that has been developed for the Strategic De-confliction system presented in this dissertation. In the paper it is presented a MTCD system that uses time-based separations to dynamically synchronize the traffic that enters into a TMA and start the approach and landing phases. One of the main contributions of this paper is the introduction of Spatial Data Structures as a way to efficiently manage and store spatial information. The SDS allows having a complete 4D description of the TMA sector, thus taking into account the entire planned/expected trajectories of the arriving flights. So, decisions can be efficiently made in real-time with a (potential) coordination among different Decision Support Tools (e.g. AMAN/DMAN).

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A Medium Term Conflict Detection and Resolution system for Terminal Maneuvering Area based on Spatial Data Structures and 4D Trajectories

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ABSTRACT

In this paper an efficient Medium Term Conflict Detection and Resolution (MTCD&R) approach based on 4D trajectories to solve conflicts in a Terminal Maneuvering Area (TMA) is presented. The conflict detection subsystem (CD) is based on a Spatial Data Structure (SDS), avoiding non-efficient pairwise trajectory comparisons, and using a simplified wake vortex modeling through 4D tubes to detect time-based separation infringements between aircraft. The conflict resolution subsystem (CR) solves the detected conflicts with an efficient and dynamic 3D allocation of the arrival routes that takes into consideration the execution of Continuous Descent Approaches (CDAs). Algorithms have been tested with several stressing traffic scenarios (rush hour and saturation rush hour) taking place in a 3D simulation model of Gran Canaria Extended TMA. The resulting conflict-free trajectories have been validated for flyability conformance both with real A380 FMS avionics and with a certified B738 Full Flight Simulator. A new CR performance metric to measure the degree of runway utilization is also proposed in order to enable comparisons between different MTCD&R systems. Finally, a discussion about strengths and limitations of the algorithms for reducing controller's workload while increasing airspace capacity of the future Single European Sky is outlined.

1. Introduction

The European Commission (EC) and the European Organization for the Safety of Air Navigation (EUROCONTROL) started in 2005 a program called SESAR (*Single European Sky ATM Research*) whose main goal is to modernize the technologies, avionics and procedures used in the European Air Traffic Management (ATM) system in order to: improve *predictability* throughout the whole system, increase *capacity*, *productivity* and *safety* of the ATM, and reduce environmental *noise* and *emissions* (SESAR Consortium, 2007, 2009).

One of the most important challenges to reach these targets consists on the introduction of the Trajectory Based Operations (TBOs), which implies the use of 4D trajectories (trajectories defined in the three spatial dimensions together with a time-stamp), also known as Business Trajectories (BTs) in the SESAR's terminology for civil flights (Cook, 2010). The required technologies to enable and support this new ATM paradigm include, among others, precise navigation equipment (P-RNAV) based on satellite technologies (GNSS) (Civil Aviation Safety Authority (Australian Goverment), 2006; EUROCONTROL, 2007a, 2007b), and aircraft-state information broadcasting and self-separation systems (ADS-B) (EUROCONTROL, 2007a).

With regards to the capacity of the ATM, nowadays the high volume of air traffic observed in Europe, combined with the current procedures used to manage the air traffic flows, causes the saturation of several air sectors during most confluent

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hours, particularly in those Terminal Maneuvering Area sectors (TMAs) at where the most demanded airports are located (EUROCONTROL, 2001; NATS, 2009; SESAR Consortium, 2009).

Over decades, air traffic controllers have been able to maintain a safe and orderly flow of air traffic in TMAs, using via-voice communications and traditional management operations, such as FIFO landing sequencings and aircraft in *holding procedures* (a predetermined maneuver which keeps an aircraft within a specified airspace while awaiting further clearance; see Fig. 1), operations mainly based on ICAO (International Civil Aviation Organization) procedures (ICAO, 2005, 2007; Castelli et al., 2010).

However, when the number of trajectories and the interactions among them are relatively high within the TMA (i.e. *high-complexity terminal operations* occur, in terms of SESAR), the task-load of controllers is then intensified, usually up to saturation, thus provoking the congestion of the sector (SESAR Consortium, 2007). As consequence, more frequent and longer holding trajectories are observed nearby the airports, which results on important extra fuel consumption and pollution (SESAR Consortium, 2008; NATS, 2009). In addition, delays may be affecting to takeoff and landing operations, which quickly propagate backwards and may also affect other TMAs and the whole ATM (i.e. TMAs are currently one of the main bottlenecks of the ATM system) (Xu et al., 2005; EUROCONTROL, 2008a). Considering that it is forecasted an increment of the air traffic flows in a factor of 2× or 3× by 2030 (EUROCONTROL, 2008a, 2008b), it is clear the necessity of finding new ways to increase the current ATM capacity.

To achieve the needed threefold capacity it is required to improve management procedures and aircraft operations in order to ensure a perfect synchronization of all air traffic flows, particularly improving the runway's throughput (minimizing in this manner the average delay per aircraft and its negative effects), and reducing the task-load of air traffic controllers, specially during high-complexity terminal operations (EUROCONTROL, 2008b; Djokic et al., 2010).

Medium Term Conflict Detection and Resolution systems (MTCD&R) are planning tools designed to help controllers managing air traffic flows at tactical level (medium term), providing with real-time information about possible future conflicts (understanding a conflict as a loss of due separation between two or more aircraft (ICAO, 2007; EUROCONTROL, 2006)) within a foreseen time-window of 20–30 min, and also providing with possible ways of solving those conflicts (EUROCONTROL, 2006; SESAR Consortium, 2009).

In this paper it is presented an efficient MTCD&R approach for TMA using a simplified wake vortex envelope model (i.e. 4D tubes enveloping the worst-cases of the stochastic vortex behavior) to detect conflicts among 4D trajectories taking into consideration the current time-based separation standards. Resolution amendments are then computed in order to synchronize and merge the traffic approaching to an airport, giving priority to obtain a good runway throughput (without misleading safety) while allowing the execution of efficient aircraft descent profiles (i.e. CDAs).

The concept of operation of this research assumes convergent traffic to a single runway only, with an aircraft mix of Heavy and Medium categories (according to ICAO vortex categorization) and under no-wind conditions. To better introduce the key aspects of the research, only the nominal model of the MTCD&R algorithms is presented (i.e. with a limited set of uncertainty sources under consideration), thus: a) a simplified wake vortex behavior is specified, b) perfect or near-perfect execution of 4D trajectories is assumed, and c) no relevant weather effects nor other classes of perturbations is considered. A brief discussion about how uncertainty may affect the nominal model is outlined in Section 6.

These MTCD&R algorithms were initially designed under the ATLANTIDA project (leaded by Boeing Research & Technology Europe) in order to detect tactical conflicts among a set of UAVs maneuvering under Free-Flight conditions. After that, same algorithms were scaled to detect and solve conflicts among Heavy and Medium aircraft in Canary Islands and obtained results are presented in this paper. More recently, the STREAM research project (a SESAR's WP-E leaded by ALG-INDRA) has also adopted some of the ideas presented in this paper, specifically the usage of Spatial Data Structures for conflict detection and resolution at strategic level (long term) with a seamless coordination with the tactical level (medium term) (Ranieri et al., 2011).

2. State of the art

2.1. Description of a conflict

There are different types of conflicts. ICAO 6108873-DOC-4444 documentation (ICAO, 2007) describes the minimum safety distances to be preserved between aircraft. It defines the required vertical, horizontal and temporal safety distances

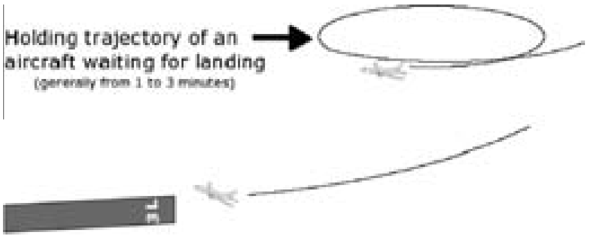


Fig. 1. Holding procedure.

to minimize the probability of collision. Temporal safety distances, which state the necessary lapse of time in which an aircraft cannot cross the same space than a previous aircraft, are also required to avoid dangerous encounters with the turbulences (wake vortex), generated by previous aircraft.

For simplicity purposes, in this paper only temporal safety distances to avoid vortex encounters in TMA are considered, which is of interest of SESAR's Service Level 5 (spatial safety distances can also be afforded by setting the same algorithms presented in this paper).

Different temporal distances are defined depending on the aircraft weight categories. Heavy/Medium aircraft generate bigger and stronger vortexes than other smaller aircraft, especially in low altitudes and at slow speeds (i.e. most dangerous vortex encounters occur during Heavy/Medium taking-off and landing operations). Vortexes remain in the air form 80 s to 150 s and sink down up to 1000 ft (300 m) under the aircraft that generated them (see Figs. 2 and 3). Vortexes spread laterally no more than twice the wingspan of the aircraft (which is about 60 m in case of biggest Heavy-class aircraft like B777). Lateral winds can move the vortex from its original position (Dole, 1994; Blajev, 2006); no-wind or soft-wind conditions are considered in this research, thus vortexes may be assumed to remain static with respect the aircraft trajectory in the horizontal plane (dynamic and uncertain behavior could be also managed; see Section 6 about Uncertainty).

2.2. Conflict categorization

When a conflict is detected it can be classified into several different categories (Isaacson and Robinson, 2001; Isaacs and Brooks, 2008). Since only convergent traffic is considered in this paper (all the aircraft flying towards a single runway), the classification of the conflicts can be simplified in two categories, the *catch-up* type and the *merging* type.

A *catch-up* conflict occurs when there are two aircraft following the same path and the trailing aircraft is speedy enough to catch the leading aircraft, inducing a safety distance infringement.

A *merging* conflict occurs when two aircraft coming by different routes find each other in a merging point of these routes, trespassing the required safety distances. Note that in this case, it is not a necessary condition that the trailing aircraft flies at higher speed than the leading aircraft.

2.3. Basic aspects of MTCD&R systems

MTCD&R systems can be designed separately as two different but coordinated subsystems, one of them in charge of the conflict detection (CD), and another one in charge of the conflict resolution (CR). Both subsystems can be classified according to the way they handle detection/resolution when multiple conflicts among two or more trajectories happen. It is referred as a *pairwise strategy* when the algorithms sequentially detect/solve considering the minimum safety distances between each pair of trajectories, or it is referred as a *global strategy* when the entire traffic situation is examined simultaneously (Kuchar and Yang, 2000).

Pairwise-based algorithms are simple and easy to code but imply high inefficiencies in computational terms when a considerable amount of aircraft are processed (Reif and Sharir, 1985; Chiang et al., 1997).

Currently, CD algorithms that are implemented in operational MTCD applications (CTAS, FASTI, iFACTS, ERATO or VAFOR-IT, among others) are mainly based on pairwise strategies (EUROCONTROL, 2002a, 2007b, 2010). Automated CR tools are currently under development, but early operational applications are also based on pairwise strategies (EUROCONTROL, 2002b, 2007c; Kupfer et al., 2008).

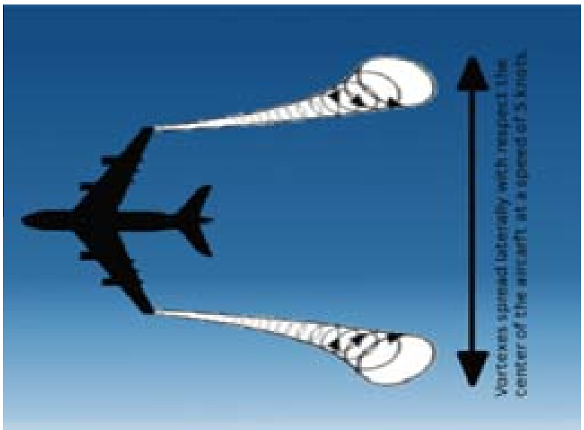


Fig. 2. Top view of vortex.

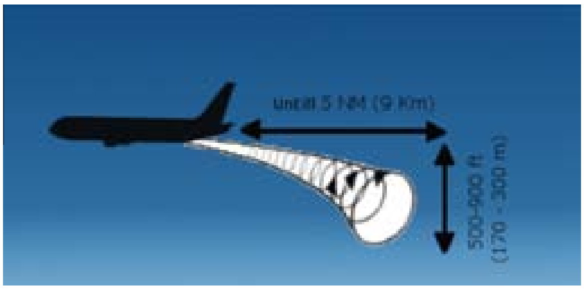


Fig. 3. Lateral view of vortex.

On the other hand, SESAR's Service Level 5 is defined with the use of time-based aircraft separations in the TMA operations, set to avoid aircraft instabilities due the *wake vortex* (turbulences) encounters (SESAR Consortium, 2008; Cook, 2010). Furthermore, FLYSAFE and WAKE4D projects also stated the importance of taking into account wake vortex hazards not only in take-off and landing operations but also in cruise traffic (Desenfans et al., 2007; Group for Research in Turbulence and Vertical Flows, 2010). The implementation of temporal distances for safety factors could provide important benefits to minimize airspace latent capacity.

An efficient CD algorithm is presented in this paper, which allows managing either spatial or temporal distances, with excellent computational performance, and storing the whole state space of the problem (characteristic that opens the possibility to design new CR algorithms that take advantage of this crucial information). In this paper, the algorithm has been set to work with time-distance separations by using a time-representation of the wake vortex generated by aircraft. The CR will take relevant data from the state-space stored in the CD in order to generate resolution maneuvers that solve the conflicts.

3. CD algorithm

3.1. Representation and storage of spatio-temporal information

The main objective of a CD system is to detect conflicts between trajectories and inform the CR system. The CR system will need a minimum amount of information about the conflicts for the resolution process. The idea behind the CD proposed in this paper is similar to take a "snapshot" of the scenario in where the aircraft execute their trajectories, providing in this manner to the CR system with the required information.

As happens with digital snapshots, first it is necessary to discretize the information in order to make it computer-tractable and store it in a digital database. Discretization will convert the continuous space of a certain scenario into a set of pixels that stores a discrete approximation of the original scenario.

It is important to point out that, by sorting the 4D information in a spatial structure, the information of a certain place can be easily stored/recovered into/from a database applying simple mathematical formulas. Concretely, the (discretized) units of information of the database can be sorted according to the (discretized) spatial positions they occupy in the space.

This kind of databases storing relevant information (i.e. state-space variables) sorted according to its position within a certain spatial region is called Spatial Data Structures (SDS) (Samet, 1989, 1990; Reynolds, 2000, 2006). The name of the SDS reflects the fact that the proper structure of the database stores the information about the spatial position (the coordinate) that a certain element/object occupies in the real world.

Fig. 4 shows a graphical representation of an SDS. A SDS can be thought as a mesh of discrete points distributed along the space in where the state-space "snapshot" is going to be taken. Note that inside the three-dimensional SDS (the cube) there is a discretized 4D trajectory (different 3D positions of an aircraft in different discrete time steps).

In this research the sampling rate to discretize the temporal dimension of a trajectory is constant, so the spatial distance between positions depends only on the speed of the aircraft, whereas the relative positions of the waypoints depend on the heading of the aircraft.

Wake vortex generated from these trajectories can be bounded, in a given instant, with a time-stamped sphere containing (within a required confidence interval) all the air turbulences that the other aircraft should avoid. Note that this 4D object (the sphere) does not represent the real position and rotation of a vortex but rather it represents a "container" or "envelope" that fits the worst-cases of the vortex behavior in a given instant, within reasonable certainty, considering the stochastic nature of this physical phenomenon. In addition, since an aircraft flying is always moving, and since the vortex is dynamically generated with the movement of the aircraft, the time-projection of the sphere describes a cylindrical shape (or "tube") when the real and continuous trajectory is considered instead of the discrete one. Note that modeling the wake vortex with a 4D enveloping tube is an oversimplification of the real behavior of the underlying fluid dynamics of this phenomenon, but this basic shape (the tube) provides with enough precision about the vortex behavior for conflict detection purposes, while at the same time it ensures a good algorithm performance due to the avoidance of complex fluid dynamic simulations. Similar

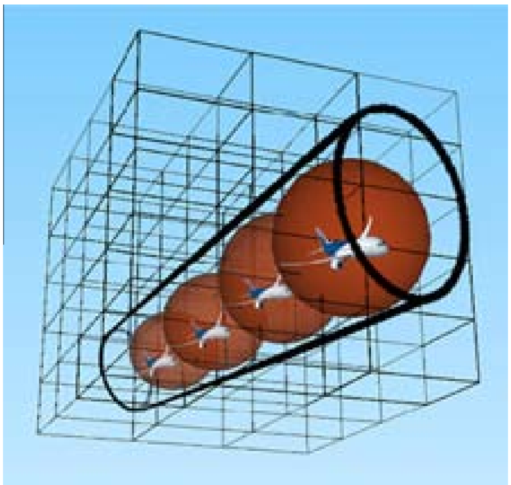


Fig. 4. Sample of SDS and a 4D trajectory.

(although more precise) modeling of the vortex by means of a 4D enveloping tube has been performed within the WAKE4D project (Group for Research in Turbulence and Vertical Flows, 2010).

In order to store the tube envelope (originally continuous), only those parts of the tube matching with the discrete coordinates (i.e. matching with a vertex of the SDS's bins) will be stored. Therefore, a discrete representation of the original tube will be stored inside the database (Hearn and Baker, 2006).

The total memory positions in the SDS database (*totalMemPos*) can be calculated with:

$$totalMemPos = X \cdot Y \cdot Z \tag{1}$$

being X, Y and Z the maximum number of discrete coordinates (i.e. the order) of each spatial dimension, respectively.

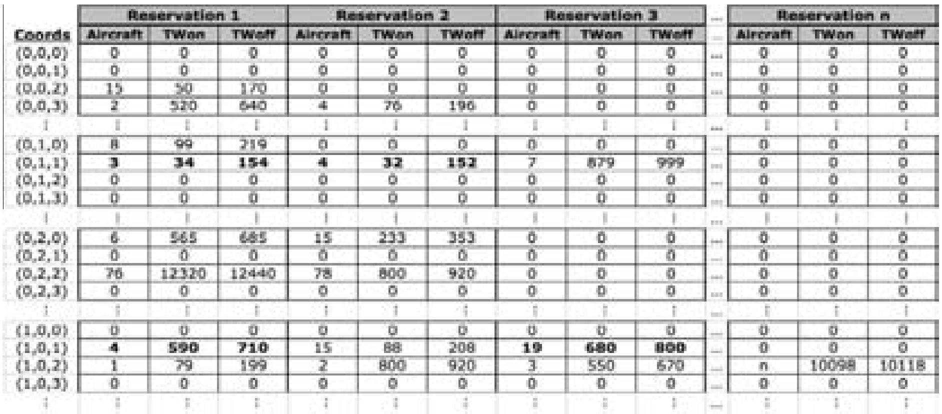
Since the discrete coordinates are sorted in a sequential order in the database (see Fig. 5), they can be easily accessed (for writing/reading) applying the following equation:

$$memPos(x,y,z) = x \cdot Y \cdot Z + y \cdot Z + z + 1 \tag{2}$$

being *memPos* a unique memory position inside the database that stores the information of a particular coordinate (x,y,z), with $x \in [0, X-1]$, $y \in [0, Y-1]$ and $z \in [0, Z-1]$.

For instance, consider a sector of size 500 × 500 × 10 km^3 with discrete coordinates separated every 100 m. According to (1) this sector can be represented by a database with 5000 × 5000 × 100 = 25 × 10^8 memory positions (note that each *XY* plane dimension of the SDS fits 500,000 m/100 m = 5000 discrete coordinates whereas the vertical dimension fits 10,000 m/100 m = 100 discrete coordinates). For instance, among these memory positions, the unique memory position (i.e. row of database of Fig. 5) corresponding to coordinate (x = 40, y = 35, z = 80) is:

$$memPos(40,35,80) = 40 \cdot 5000 \cdot 100 + 35 \cdot 100 + 80 + 1 = 20,003,581 \tag{3}$$



	Reservation 1			Reservation 2			Reservation 3			…	Reservation n		
Coords	Aircraft	TWon	TWoff	Aircraft	TWon	TWoff	Aircraft	TWon	TWoff	…	Aircraft	TWon	TWoff
(0,0,0)	0	0	0	0	0	0	0	0	0	…	0	0	0
(0,0,1)	0	0	0	0	0	0	0	0	0	…	0	0	0
(0,0,2)	15	50	170	0	0	0	0	0	0	…	0	0	0
(0,0,3)	2	520	640	4	76	196	0	0	0		0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	…	⋮	⋮	⋮
(0,1,0)	8	99	219	0	0	0	0	0	0	…	0	0	0
(0,1,1)	**3**	**34**	**154**	**4**	**32**	**152**	7	879	999	…	0	0	0
(0,1,2)	0	0	0	0	0	0	0	0	0	…	0	0	0
(0,1,3)	0	0	0	0	0	0	0	0	0	…	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	…	⋮	⋮	⋮
(0,2,0)	6	565	685	15	233	353	0	0	0	…	0	0	0
(0,2,1)	0	0	0	0	0	0	0	0	0	…	0	0	0
(0,2,2)	76	12320	12440	78	800	920	0	0	0	…	0	0	0
(0,2,3)	0	0	0	0	0	0	0	0	0	…	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	…	⋮	⋮	⋮
(1,0,0)	0	0	0	0	0	0	0	0	0	…	0	0	0
(1,0,1)	**4**	**590**	**710**	15	88	208	**19**	**680**	**800**	…	0	0	0
(1,0,2)	1	79	199	2	800	920	3	550	670	…	n	10098	10118
(1,0,3)	0	0	0	0	0	0	0	0	0	…	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	…	⋮	⋮	⋮

Fig. 5. SDS content example (reservations in bold are in conflict).

Note that the first memory position of the database belongs to coordinate $(0, 0, 0)$ and the last position to coordinate $(X-1, Y-1, Z-1)$:

$$memPos(0,0,0) = 0 \cdot 5000 \cdot 100 + 0 \cdot 100 + 0 + 1 = 1 \tag{4}$$

$$memPos(4999,4999,99) = 4999 \cdot 5000 \cdot 100 + 4999 \cdot 100 + 99 + 1 = 25 \times 10^8 \tag{5}$$

To optimize the CD run-time performance it is important to implement the SDS in the computer *main memory* (i.e. RAM memory) since the access-time to any memory position is constant and faster than with any kind of external memory devices. *Granularity* or *resolution* of the SDS is the distance between discrete points of the SDS. To determine the optimal separation between SDS points is not an easy matter, and there is no a general method to do that. Note that the excess of resolution may lead to a loss of computer performance as well as to an inoperable amount of main memory requirements, whereas a lack of resolution may lead to lose some important objects of the space, thus missing the detection of some existing conflicts (i.e. *false negative* errors). Factors as the size of the physical airspace to model, the size of the objects to be stored in the database, the speed at what these objects move, the quantity of memory available in the computer, and the speed of execution of the algorithms, among other factors, should be considered to determine the granularity of the SDS (Ruiz and Piera, 2009).

In this research, a spatial discretization of 100 m between points of the discrete mesh has been considered. Such granularity ensures, for the purposes of this paper, a good trade-off between the quality of the information stored in the SDS for conflict detection purposes (i.e. no missed conflicts) and the run-time performance of the CD&R algorithms. This granularity has taken into account the size of the 4D tube used as envelope of the wake vortexes (with considered diameter of 300 m since it is the maximum assumed vortex sinking), the aircraft speed (generally over 100 m/s) and the quantity restrictions of the RAM memory (4 GB in the testing computer) as well as the size of the scenario used for simulations (see Section 5).

Note that a radius of 300 m for the tube envelope is big enough to also fit the horizontal dimensions of the two vortices generated by largest Heavy aircraft (i.e. around 120 m maximum) and leave relevant looseness to lead with navigational tracking errors. The radius of the 4D tube-envelope can be increased in case of stronger and changing winds, in order to model the stochastic position of the vortex (see Section 6 about Uncertainty).

3.2. Conflict detection

According to the trajectories to be flown by aircraft (and assuming that weather conditions are known), a 4D tube is built as a 4D container that envelops, within a reasonable confidence interval, the generated wake vortex, considering intrinsic uncertainties in position and duration. Dimensions of the 4D tube should be specified according to the current knowledge and prediction ability of the wake vortex phenomenon.

Once a discrete tube has been built (rounding the discrete surface of the tube to the nearest discrete coordinates), it is ready to be stored in the SDS. Every discrete point that conforms the tube is identified in a unique location (a discrete coordinate), which can be found in the SDS in form of a memory position.

Every data stored into the SDS can be interpreted as a reservation (or "booking") of an aircraft, which intends to use a spatial resource (the coordinate) for a certain period of time. Thus, minimum information to be stored is the *aircraft id* (which is the object that occupies the discrete coordinate of the SDS) and the *time-window* at which the coordinate will be occupied by the corresponding safety tube of the aircraft. If two or more aircraft want to use the same coordinate at the same time (or during overlapped time-windows), then it means there is a conflict between their trajectories.

Note that storing the time (time window) makes the SDS to be a 4D snapshot of the real world. Time windows can be stored explicitly, with the couple [vortexOn-time, vortexOff-time], or implicitly, since it can be stored only the vortexOn-time and, when needed, it can be calculated the vortexOff-time through adding a constant interval of time to the vortex-On-time. For example, in the case of modeling turbulences, it is possible to store implicit time-windows, as the turbulences are considered remaining in the air during a maximum constant time period of 120 s (for simplicity only Heavy aircraft are considered in this paper).

Fig. 5 illustrates an example of SDS content. The SDS has been implemented as a big one-dimensional array stored in a RAM memory (for efficiency purposes), but it can be conceptually drawn as a table containing as many rows as coordinates are in the modeled airspace and as many columns as aircraft/trajectories will be processed.

Under a scenario without holding procedures it is possible to assume that no aircraft will cross the same place more than once, so only one booking per aircraft and coordinate is allowed.

Fig. 6 shows the CD algorithm, being N the number of airplanes, Wa an array storing all the tube points (3D coordinates) of aircraft a, SDS an array which represents a table with as many rows as coordinates in the modeled airspace and N columns, and verifyTwoOverlap(booking1, booking2) a function returning true if two time windows overlap.

At the moment of storing a tube-point the algorithm reads the first column. If its value is zero it means that no other aircraft intend to use such a coordinate, so this spatial resource can be booked without conflict. If the first column is not empty, then the algorithm compares the (explicit or implicit) time windows. If their time-windows are overlapping, then a conflict is detected and the CR system is informed. If the time windows are not in conflict, it means that the coordinate might be booked in the following column. In next columns applies sequentially the same procedure.

Therefore, comparisons among aircraft are only performed in those locations that will be used by more than one aircraft, and always limited to the maximum amount of aircraft using those coordinates, which usually is much less than the total number of trajectories in the scenario. Thus, the SDS acts like a "spatial prune" avoiding the pairwise strategy and linearizing the temporal performance of the algorithm (see next section).

Tubes convexity property has been used to ensure that all the possible conflicts will be detected on the surface of the tubes, so important computational time savings are possible since only the surface of the tubes are processed.

3.3. Proof of linear temporal complexity and non-pairwise behavior

A pairwise CD algorithm is characterized because it sequentially processes all the trajectories by comparing the distance separation among all the possible pairs in which these trajectories can be grouped. A formal complexity analysis of a simple pairwise algorithm can be made by combinatorial analysis: the maximum amount of comparisons among different pairs of trajectories that can be formed with N aircraft (without repetition) is $\frac{N(N-1)}{2}$. Therefore, it implies a temporal complexity order of the algorithm of $O(N^2)$. Same results can be found in Isaacson and Erzberger (1997).

It is important to note, that the required $\frac{N(N-1)}{2}$ comparisons is done for each time-instant in which a 4D trajectory is sampled (e.g. 4D discrete trajectories are sampled every 1 s steps in this paper so, for each sample a pairwise comparison with the same time-stamped sample of other trajectories is required). Therefore, as the number of computations is always the same at each time-step (i.e. there is no best-case nor worst-case), the global algorithm complexity consists on an *exact* quadratic order, $\Theta(N^2)$.

On the other hand, the SDS-based CD is considered a non-pairwise algorithm since in order to perform the detection of conflicts the algorithm only compares – the time-windows of – those trajectories that use the same spatial resources, as it can be inferred form the complexity analysis of the algorithm.

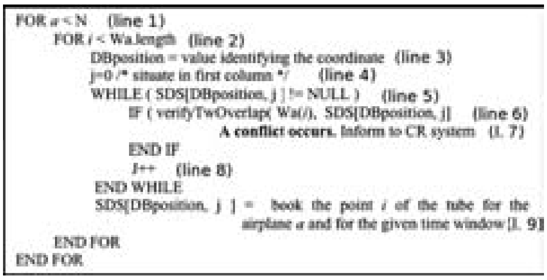
The complexity analysis of the SDS-based CD algorithm, due to its particular design, requires another kind of complexity study different from the combinatorial analysis. Following the methodology of Baase (1988), Cormen et al. (1997), Aho et al. (1998), and Peláez Sánchez (2003) a demonstration of linear complexity (and non-pairwise behavior) is done through the *average case* of the temporal algorithm's complexity. To study the average-case a probabilistic analysis is performed, which allows observing how the probability of a given 3D airspace coordinate (and thus a mesh-point of the SDS) of being used by *exactly all* the trajectories become smaller as the number of aircraft N grows.

Fig. 6 shows the SDS-based CD algorithm with some labeled lines. Let N be the total amount of aircraft/trajectories to process, *Wa* an array storing all the coordinates used to represent the wake vortex envelope of aircraft a (i.e. the full 4D tube), and *SDS* a bidimensional array storing all the bookings (a, i, j, and *DBposition* are indexes to move along those arrays). The number of Elementary Operations (EO) of this algorithm can be decomposed in:

- In **line 1**: 2 EO are executed, 1 for assignment, 1 for comparison and 2 additional for the end of loop.
- In **line 2**: 2 EO are executed, 1 for assignment, 1 for comparison and 2 additional for the end of loop.
- In **line 3**: 1 EO is executed.
- In **line 4**: 1 EO is executed.
- In **line 5**: 2 EO are executed, 1 for accessing the SDS, 1 for comparison and 2 for the end of the loop.
- In **line 6**: 3 EO are executed, 2 accesses to tables and 1 to call an external procedure.
- In **line 7**: 1 EO is executed, to call an external procedure.
- In **line 8**: 2 EO are executed, 1 for arithmetic operation and 1 for assignment.
- In **line 9**: 2 EO are executed, 1 for access to table and 1 for assignment.

Note that *Wa.length* indicates the *total amount of discrete coordinates that build the safety tubes of a particular aircraft/trajectory*. For simplicity of the analysis this number is assumed to be constant for all the aircraft and it is represented by L.

Let assume that all the coordinates have the same probability of being used by a given trajectory (equiprobability is assumed for simplicity of the argument, although the proof is valid for any set of probabilities, including the ones associated to



```
FOR a < N    (line 1)
    FOR i < Wa.length   (line 2)
        DBposition = value identifying the coordinate  (line 3)
        j=0 /* situate in first column */      (line 4)
        WHILE ( SDS[DBposition, j ] != NULL )     (line 5)
            IF ( verifyTwOverlap( Wa(i), SDS[DBposition, j]    (line 6)
                        A conflict occurs. Inform to CR system   (l. 7)
            END IF
            J++    (line 8)
        END WHILE
        SDS[DBposition, j ] =  book the point i of the tube for the
                            airplane a and for the given time window [l. 9]
    END FOR
END FOR
```

Fig. 6. CD algorithm.

TMA scenarios with either a prefixed structure of arrival and departure routes or with dynamic 3D routes allocation). Let C to be the *total amount of discrete (3D) coordinates* which compose a certain airspace sector, then the probability p_c of an aircraft to use a certain coordinate in a given instant of time is:

$$p_c = \frac{1}{C} \tag{6}$$

Thus, the probability p_A of an aircraft using a determined coordinate of the SDS, with a safety tube (that covers the trajectory) made of L discrete points, is:

$$p_A = p_c \cdot L = \frac{L}{C} \tag{7}$$

Finally, the probability p_N of all the N aircraft using the same coordinate (not necessarily at the same time) is:

$$p_N = (p_A)^N = \left(\frac{L}{C}\right)^N \tag{8}$$

Usually $L \ll C$ (the amount of coordinates composing a trajectory is much smaller than the amount of available coordinates in the airspace sector), so in general $p_N \approx 0$. It means that in average (and considering realistic scenarios) it is unlikely that the SDS-based CD compares among all the pairs of trajectories in each time-step of the trajectories, since it will only establish comparisons among those trajectories that use the same spatial resources. Therefore, it can be stated that the SDS-based CD algorithm is *non-pairwise*.

In addition, note that when the amount of aircraft N increases, the probability of *exactly all* of the trajectories using a same 3D coordinate becomes smaller, being 0 at the limit:

$$\lim_{N\to\infty} p_N = 0 \tag{9}$$

It can also be observed that the greater is the size of the sector, C, and the fewer is the size of the trajectories, L, the lower is the probability of coincidence of *exactly all* the N aircraft using a certain coordinate, which is congruent with intuition.

Adding probability p_N to the complexity analysis of the algorithm, the average-case for N aircraft/trajectories can be computed with $\widetilde{K} = p_N \cdot N$ as follows ($\widetilde{K}$ is the average amount of executions of the *while* loop in line 5 of Fig. 6):

$$\begin{aligned} T(N) &= \left[\sum_a^N \left(2 + \sum_i^L \left(4 + \sum_j^{\widetilde{K}} 8 + 4\right) + 2\right) + 2\right] \cdot t_{EO} = \left[\sum_a^N \left(2 + \sum_i^L \left(8 + 8\widetilde{K}\right) + 2\right) + 2\right] \cdot t_{EO} \\ &= \left[\sum_a^N (4 + (8 + 8\widetilde{K})L) + 2\right] \cdot t_{EO} = [8L\widetilde{K}N + (8L + 4)N + 2] \cdot t_{EO} \end{aligned} \tag{10}$$

being t_{EO} the average time needed to process an Elementary Operation.

Since in general $\widetilde{K} \ll N$ (being $\widetilde{K} = 0$ asymptotically), the average upper bound of complexity is $T(N) = O(\widetilde{K}N + N) = O(N)$. And since the average upper bound and the lower bound (i.e. the *best case*) belongs to the same order (lower bound occurs when $\widetilde{K} = 0$) it means that the exact order of complexity of such an algorithm is linear, $\Theta(N)$ for most scenarios (for those – unrealistic – scenarios in which $O(L) \cong O(C)$ or $L \geqslant C$ the proof of linearity is not valid and thus the algorithm behaves as a pairwise algorithm).

Empirical analysis have validated the linear behavior of the algorithm, measuring the CD performance among different sets of trajectories all of them lasting 30 min and coexisting during the same time-window in a TMA in which the $L \ll C$ condition applied. For this particular scenario, Eq. (10) can be approximated with the following formula (see Fig. 7):

$$T(N) = N \cdot t = N \cdot 5\ \text{ms} \tag{11}$$

being t the average processing-time of each 4D trajectory, which includes the construction, rotation and placement of the 4D tubes that bound the aircraft vortex ($t = 5$ ms for this research).

In addition, the same scenarios were computed and compared (see Fig. 7) with a standard pairwise algorithm whose processing-time, T, can be approximated as a function of the number of aircraft, N, by:

$$T(N) = \frac{N(N-1)}{2} \cdot p \cdot t \tag{12}$$

being p the percentage of pairs not pruned by altitude pre-filters and t the average processing-time of each 4D trajectory comparison, which mainly depends on the computer processor's speed ($t = 40\ \mu$s for this research).

It should be noted that the value of p strongly depends on the traffic patterns of the considered scenario. Nevertheless, due to the different algorithm runtime behaviors (i.e. linear vs. quadratic behavior), even when considering a low value for p (for example, $p = 0.4$ for some TMAs, according to Isaacson and Erzberger (1997)) the linear behavior of the SDS-based algorithm may still take advantage over a quadratic behavior when considering certain amount of aircraft. However, conclusions should be extracted carefully from Fig. 7, since the algorithms used for the comparison are qualitatively different and thus they cannot be directly compared only by their runtimes (i.e. the SDS-based algorithm performed conflict detection

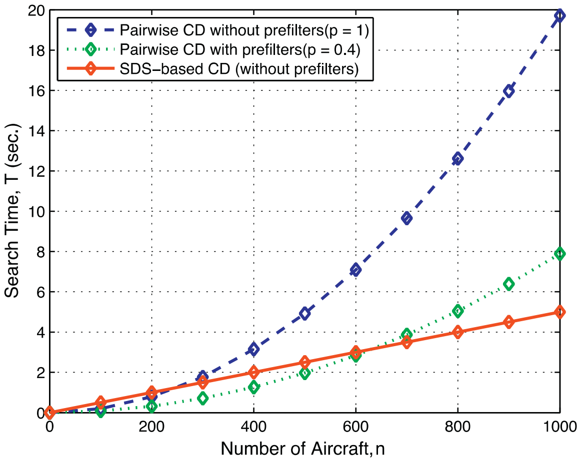


Fig. 7. Empirical performance results.

comparing temporal distances among 4D tubes representing wake vortexes, whereas the standard pairwise algorithm used spatial distance comparisons among aircraft point-mass positions).

4. CR algorithm

Some unplanned incidents may occur (i.e. perturbations), due to advances or delays introduced in the times of arrival or departure of the aircraft, fostering conflicts to emerge between trajectories of aircraft flying within the same TMA.

In case of arrivals, and due to the limited capacity of the runways to absorb the incoming traffic, perturbations during peak hours can rapidly lead to the congestion of the TMA, further augmenting the probabilities of conflicts between trajectories and thus generating a more complicated task-load for controllers. Thus, one of the main objectives of the CR system, apart of providing with conflict-free trajectories, is to keep the runway fed in order to take advantage of its capacity to absorb the traffic.

Holding procedures are used in order to safely handle the air traffic arriving to an airport at the same time the runway is kept fed. For example, in Heathrow airport around a 56% of the incoming traffic (1200 aircraft a day in average) are asked to wait in a holding stack typically from 3 to 10 min (EUROCONTROL, 2009; NATS, 2009). These holding procedures are effective from the point of view of safety, and even of capacity, but they embody important inefficiencies in fuel-costs and pollution-emissions terms. Therefore, one of the objectives of the SESAR project is to provide to controllers with Decision Support Systems like MTCD&R systems in order to reduce their task-load and to improve the tactical management of the airspace, especially in TMAs.

To minimize fuel costs, the strategy used by the CR proposed in this paper is to generate vectors (*path stretching*) for aircraft in conflict while minimizing the change of vertical and speed profiles with respect the Reference Business Trajectories (RBT) (Zúñiga et al., 2010). RBTs are considered the optimum trajectories since they accomplish with controller's restrictions and also take into account the business preferences of airlines.

In addition, RBTs used in this research supports an innovating descending maneuver that is known as CDA (Continuous Descent Approach), a maneuver currently spreading between airlines because of its benefits in fuel savings, and emissions and noise reduction (EUROCONTROL, 2008c).

4.1. Conflict resolution

This paper focuses on convergent scenarios, thus only two types of conflicts are considered: *catch-up conflicts* and *merging conflicts* (see Section 2.2). Catch-up conflicts can be solved both by speeding up the leading aircraft or by speeding down the trailing one (or a mix of both maneuvers with a speed variation limit of ± 5–6%). However, since CR tries to saturate the runway, it will be assumed that leading aircraft will not be able to speed up in order to not cause a catch-up conflict with prior leading aircraft, so the resolution of a *catch-up* conflict in this research will consists only on a delay of the trailing aircraft (note, however, that this resolution may propagate the conflict backwards, being necessary the same procedure to solve new conflicts).

Merging conflicts in TMA can be solved by speed changes or path stretching/shortening, with or without modification of the planned landing schedule. For simplicity, no advances are permitted between aircraft (AMAN's sequence is static), and since leading aircraft cannot speed up (because the runway is supposed to be saturated), it is possible in this simple scenario to solve *merging* conflicts also by applying a delay, same as in presence of *catch-up* conflicts. Therefore, *all conflicts in this research will be solved with a delay in trailing aircraft.*

Being t_c the *elapsed time* from the entry-time of an aircraft into TMA up to the moment this aircraft enters in conflict with a leading aircraft, and being $\bar{v}$ the *average velocity* of such aircraft during this period, it can be derived the *covered distance* by this aircraft, *d*, from:

$$d = \bar{v} \cdot t_c \tag{13}$$

As conflicts are solved through *delays in trailing aircraft*, Δt_c, an increment of *d* or a reduction of $\bar{v}$ is required (or a mix of both).

In general, modifying the speed of an airplane has greater difficulties than modifying the covered distance, due to the technical and physical limitations to accelerate or decelerate an aircraft. Moreover, a resolution based on speed changes may require not only decelerations but also accelerations (implying a higher fuel consumption). Note that similar arguments are given in (Erzberger, 2006).

Mathematically, the *new covered distance* for the resolution, d', can be calculated with:

$$d' = (\bar{v} + \Delta\bar{v}) \cdot (t_c + \Delta t_c) \tag{14}$$

being $\Delta\bar{v}$ the *increment of the average speed* (necessary to equal the speed of A_2 with the speed of A_1), and Δt_c the due *delay* to solve the conflict.

First, it is calculated the required delay for trailing aircraft, A_2, with the information about the time of the 4D coordinate in conflict that is stored in the SDS, plus adding t_{ds} seconds of the (implicit) time window (120 s in this research, for categories Heavy and Medium). Particularly, delay is calculated as:

$$\Delta t_c^{A2} = (t_c^{A1} - t_c^{A2}) + t_{ds}^{A2} \tag{15}$$

being A_1 the prior aircraft, A_2 the rear one, t_c the time of the in-conflict 4D coordinates of respective safety tubes (which are stored in the SDS) and t_{ds}^{A2} the minimum required safety distance for A_2 flying behind A_1. Extra temporal buffers could be still added to (15) due to uncertainties, e.g. due to the precision of current navigation systems that do not allow flying a 4D trajectory with exact accuracy (see Section 6 about Uncertainty).

Once A_2's delay is calculated with (15), a new 4D waypoint, named P^{Target}, can be fixed in the route of the trailing aircraft. The spatial coordinates of P^{Target} will be the same as the 4D point where A_2 had the conflict, but the time of this 4D point is changed from t_c to $(t_c + \Delta t_c)$. Thus, A_2 will arrive to P^{Target} just t_{ds}^{A2} seconds later than A_1, so the conflict will be solved at this point.

Note that to avoid future conflicts, and since the destination of both aircraft is the same, A_2 should follow exactly the same route used by A_1 from P^{Target} to runway and with the same speed profile (assumed same aircraft performance). Thus, to obtain d' it must be considered that A_2 has to converge to the same speed of A_1 from P^{Target} onwards, what ensures that A_2 will not enter in conflict with A_1 anymore, while ensuring an optimum throughput in the runway (i.e. minimum gap between aircraft). The required average speed change for the trailing aircraft to be used in (14) is calculated as follows:

$$\Delta\bar{v}^{A2} = \frac{v_c^{A1} - v_c^{A2}}{2} \tag{16}$$

where v_c^{A1} and v_c^{A2} are the *instantaneous speeds* at the time of conflict for aircrafts A_1 and A_2 respectively.

Once calculated with (14) the new distance d' to be covered by A_2 to avoid the conflict, the next step is to calculate a *distortion* in the original route of A_2 in order to find a new route with origin in P^{entry} and destination in P^{Target} such that it can be covered by A_2 at an average speed of $(\bar{v} + \Delta\bar{v})$ instead of $\bar{v}$ and in a period of time of $(t_c + \Delta t_c)$ instead of t_c.

In general, it will occur that $d' > d$, so a possible way of calculating the distortion is shown in Fig. 8.

Four waypoints are considered. P^{entry} and P^{Target} are, respectively, the point of entry to the TMA and the point where the aircraft entered in conflict. P^{mid} is a waypoint just in the middle between P^{entry} and P^{Target}. And P^{curve} is the waypoint responsible of generating the necessary distortion in the original route, forming a "curve" with two segments of length equal to $d'/2$. In this manner, aircraft A_2 will cover the exact distance needed to solve the conflict, ending its curved route in the same point where it had the conflict (P^{Target}).

Note that the new distance to be covered, d', calculated in (14), is a three-dimensional distance. To simplify, the problem is treated first in 2D (as in Fig. 8), and later it is converted again to 3D, taking into account the calculation of the Top Of Descend (TOD) of a CDA landing maneuver.

On the other hand, it also can happen that $d' < d$. This case can occur when the average speed derived form speeds convergence $\Delta\bar{v}$ is lower than the average speed of the original trajectory. In this case the resolution will consist on incrementing the average speed in order to make d' be greater until $d' = d$. Since v_0 and v_f are determined, the most efficient solution is to maintain initial speed v_0 until a certain distance Δx_1 be covered, and then to (constantly) decelerate until aircraft reach speed v_f while covering a distance Δx_2. The goal is, again, to arrive to P^{Target} in the time calculated for resolution, $(t_c + \Delta t_c)$. Fig. 9 shows the geometrical problem to solve.

In this case, it is of interest to know the distance Δx_1 along the aircraft will fly at a constant speed v_0. This track distance will be covered in a period of time $t_1 = \Delta x_1 / v_0$. Once covered the distance Δx_1 trailing aircraft has to begin decelerating with a

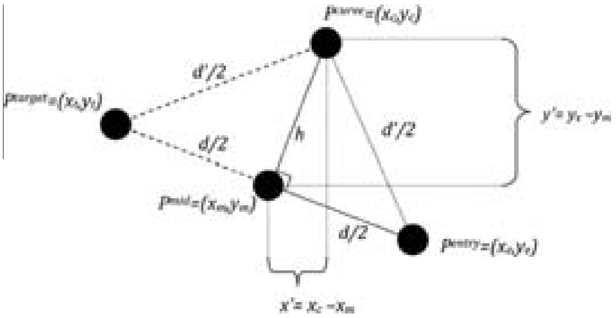


Fig. 8. The geometric problem of varying the route.

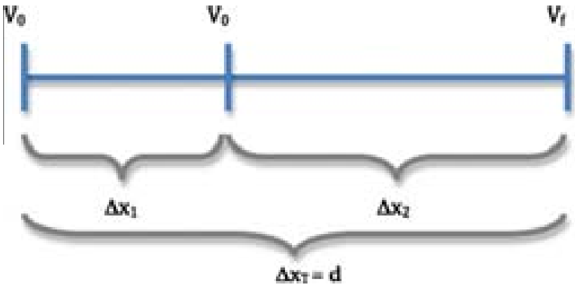


Fig. 9. The geometric problem of varying the speed.

constant rate, covering a Δx_2 distance and ending with v_f speed. This second track distance will be covered in a period of time $t_2 = 2\Delta x_2/(v_0 + v_f)$ (assumed constant deceleration). Thus, knowing that it must be accomplished the restrictions of $t_1 + t_2 = (t_c + \Delta t_c)$ and $\Delta x_1 + \Delta x_2 = d$, it is possible to obtain Δx_1 as a function of the already known parameters:

$$\Delta x_1 = \frac{v_0((t_c + \Delta t_c)(v_0 + v_f) - 2d)}{(v_f - v_0)} \tag{17}$$

Note that resolutions of the proposed approach uses a set of rule-based vectoring maneuvers that are routinely applied in current air traffic control practice since they are easily understandable by pilots as well as easily implementable by on-board autopilots which regulate the aircraft to heading and speed waypoints. Thus, in a medium-term time window, conflict scenarios can be smoothly resolved, so that they do not become near-range threats. At the same time, the proposed maneuvers minimize the change with respect the RBT, so the fuel consumption (and pollution) is heuristically minimized for each trajectory.

Note that geometrical problems have been stated considering a Euclidean 3D space (not curved space) as shown in Fig. 10B. However, for real applications the CD&R system should consider the curvature of the Earth (Fig. 10A). Since Euclidean spaces make simpler the construction of the SDS and the processing of the conflict-free trajectories, a planar projection of the Earth has been considered using a coordinate system with minimum distortion like the Universal Transversal Mercator (UTM) (Pérez Navarro et al., 2009).

4.2. Validation of flyability for conflict resolution proposed trajectories

Mechanical and physical restrictions, as for example maximum and minimum speeds, must be considered when computing the resolution trajectories for real aircraft. Recent validation experiments with real FMS avionics and with a high-precision Boeing 737-800 certified simulator (Full Flight Simulator category D) have shown that the trajectories generated by the CR algorithm are flyable with a Boeing 737-800.

The STAR (*Standard Arrival Route*) configuration of the Gran Canaria Extended TMA has been used to test the flyability of the maneuvers proposed by the CR algorithm (see Fig. 11).

According to the Spanish Aeronautical Information Publication (AIP), the nominal STARs TERTO3C and RUSIK3C are composed by the following waypoints:

- TERTO3C: TERTO, LZR, BETAN, CANIS, ENETA (IAF), LPC (FAF), RWY.
- RUSIK3C: RUSIK, FTV, FAYTA, CANIS, ENETA (IAF), LPC (FAF), RWY.

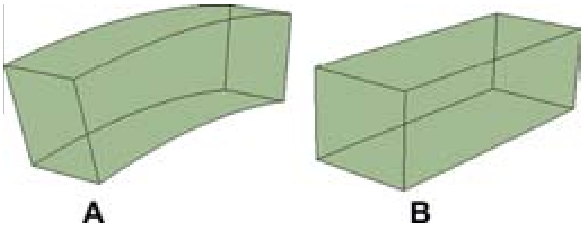


Fig. 10. TMA model considering the curvature of the Earth (A) and simplified Euclidean model (B).

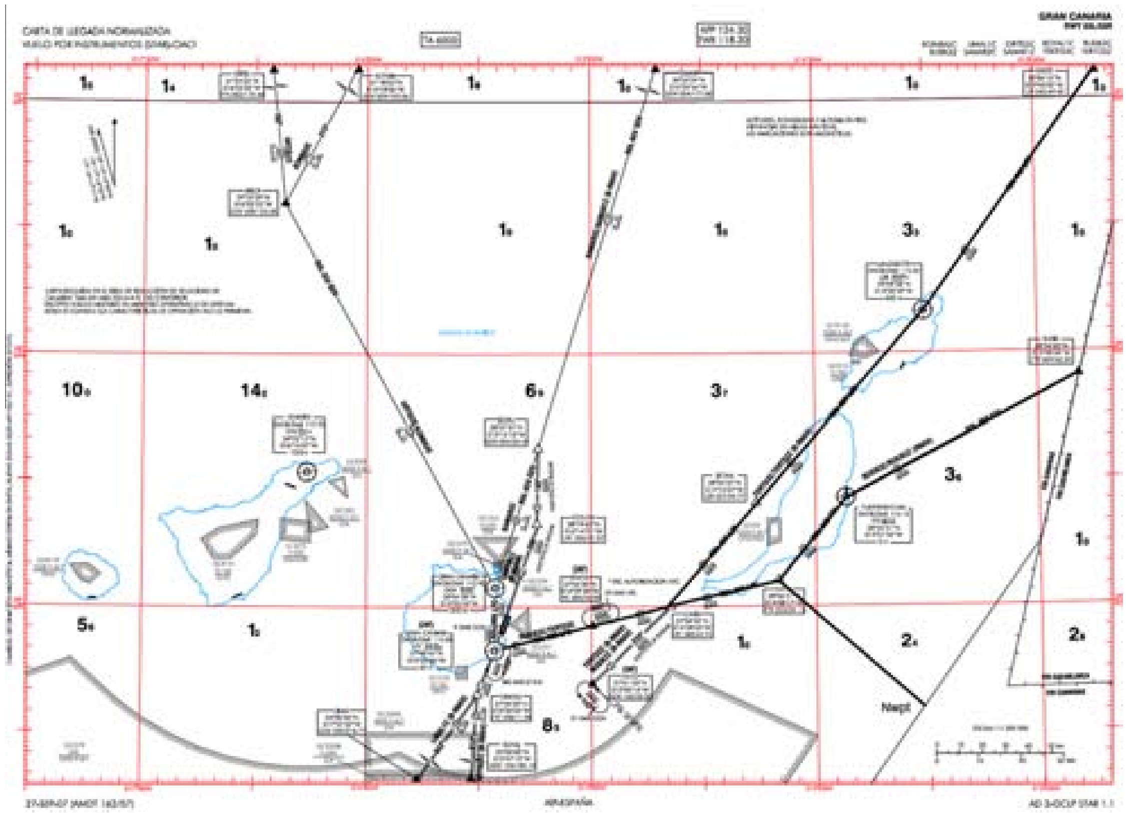


Fig. 11. Gran Canaria Extended TMA chart.

For simplicity of the validation experiment, the CR trajectories were only computed up to the Initial Approach Fix (IAF) called ENETA, since the standard approach procedures beyond this waypoint is assumed to be static and equal to the nominal trajectories computed by the FMS of the Boeing 737-800 (i.e. no changes are allowed after ENETA).

Fig. 12 shows the FMS display view of a trajectory following the nominal RUSIK3C route and Fig. 13 shows the FMS display of the same trajectory modified by the CR to fly-by a waypoint called WPT01 instead of by FTV.

Table 1 shows an example of a trajectory computed by CR to solve a conflict occurred in waypoint WPT12. Latitude, longitude, height, elapsed time, Indicated Air Speed (IAS) and True Air Speed (TAS)/Ground Speed (GS) are given for each waypoint of the trajectory (TAS and GS are equivalent in this case since no-wind conditions were considered both in the CR trajectory generation and in the validation experiments). Note that the resolution maneuver consisted on imposing an arrival time to WPT12 (applying a delay computed with (15)), while preserving at this point the same GS as the previous aircraft at the moment of flying over WPT12 (to avoid catch-up conflicts). To meet these 4D restrictions, new extra distances to be covered, as well as some Ground Speed changes were required (computed with (14)). Some extra restrictions have been taken into consideration to maintain a constant descent speed (300IAS, or equivalently Mach 0.79 at FL300) and to compute the Top Of Descent for a CDA maneuver. Waypoint TOD11 indicates the Top Of Descent computed by CR considering the

Fig. 12. Nominal RUSIK3C route.

Fig. 13. Modified RUSIK3C route example.

performance of a B738. WPT11 was computed as a turning point (P^{curve} of Fig. 8) in order to make the trajectory matching with all the restrictions (see Fig. 14).

In Fig. 15 it can be observed the KIAS speed (or the equivalent Mach number) and the Flight Levels computed by FMS for each waypoint. Fig. 16 shows the Expected Time of Arrival (ETA) in format HHMM at the moment of the simulation. Both figures reflect the same information as Table 1.

Table 2 provides information of another CR resolution trajectory example but now starting at TERTO instead of at RUSIK. Figs. 17–19 illustrate, respectively, the trajectory profile displayed in the FMS, the KIAS and Flight Level for every waypoint, and their corresponding ETAs.

Table 1
RUSIK3C modified by CR.

	Lat.		Long.		ft	*t* (min)	IAS (kt)	TAS/GS (kt)
RUSIK	28°	54.4′	−12°	49.0′	30,000	0.0	300	466
WPT11	28°	04.3′	−13°	36.0′	30,000	8.4	300	466
TOD11	28°	02.0′	−14°	02.7′	30,000	11.4	300	466
WPT12	27°	57.8′	−14°	49.0′	17,700	17.3	300	393
ENETA	27°	55.5′	−14°	59.6′	13,700	18.1	300	350

This validation experiment confirms that the current CR algorithm generates flyable resolution trajectories for B738. It is important to point out, though, that due to the fact that the ETAs are rounded to minutes in the FMS (17 min for WPT12 and 24 min for WPT02 according to Figs. 16 and 19) it is not possible to verify the total fulfillment of ETAs computed by CR with respect the ETAs obtained in the simulated flight. However, these ETAs coincide if rounded to minutes (17.3 for WPT12 and 24.4 for WPT02, as shown in Tables 1 and 2).

Several authors used GS in their CR algorithms since it relates the position and speed of all aircraft to a common and static coordinate system, for example (Erzberger, 2006). In our research, since no-wind conditions were considered, GS has been used not only to maintain aircraft separation but also to compute the CDA trajectories with constant IAS. However, in presence of noticeable wind, the CR algorithm should be updated to compensate the GS and TAS differences during the computation of the CDAs whilst respecting the GS restrictions to maintain the due aircraft separation.

4.3. Integration of the CR and CD systems

Each time a conflict is detected in the CD module the CR generates a new 4D trajectory for the following aircraft with a due delay to solve the conflict with the prior aircraft. This new trajectory is then passed again to the CD module and stored in the SDS. The process is repeated until no conflict is detected with other trajectories (in this research it has been generally reached in the first iteration).

On the other hand, since the processing of information expends resources (time and memory), it is convenient to adapt the "capture" of information of the CD in order to process only the minimum and relevant information for the CR (Ruiz and Piera, 2009).

In this research, the "capture" of the CD has been limited to the aircraft *id*, the implicit *time window* and the *coordinates* used by the aircraft (coordinates are stored in the structure of the SDS). Note that for a more sophisticated CR system, other data about the space state might be interesting and could be also stored in the SDS (e.g. probabilistic data, weather information, etc.).

Fig. 14. Modified RUSIK3C route.

```
   ACT RTE   LEGS      1/3
  284°      0.3NM
 RUSIK          .790/FL300
  270°       65NM
 WPT11          .790/FL300
  270°       24NM
 TOD11          .790/FL300
  270°       41NM
 WPT12           300/FL177
  263°      9.7NM
 ENETA           300/FL137
  RNP/ACTUAL---------------
 2.00/0.02NM    RTE DATA>
 DRAG REQ AFTER ENETA
```

Fig. 15. B738 FMS data.

```
   ACT RTE   DATA    1/3
              ETA      WIND
RUSIK       1524z  000°/ 0
WPT11       1532z  000°/ 0
TOD11       1535z  000°/ 0
WPT12       1541z
ENETA       1542z
----------------DATALINK
<LEGS               FAIL
DRAG REQ AFTER ENETA
```

Fig. 16. B738 FMS data (ETAs).

Table 2
TERTO3C modified by CR.

	Lat.		Long.		ft	*t* (min)	IAS (kt)	TAS/GS (kt)
TERTO	30°	06.3′	–12°	43.0′	30,000	0.0	300	466
WPT01	29°	27.1′	–14°	19.6′	30,000	11.9	300	466
TOD01	28°	37.8′	–14°	35.9′	30,000	18.5	300	466
WPT02	27°	57.9′	–14°	48.8′	17,800	24.4	300	382
ENETA	27°	55.5′	–14°	59.5′	13,800	26.0	300	350

Fig. 17. Modified TERTO3C route.

5. Simulation and results

In order to test the CD&CR algorithms and the developed implementation several simulations has been executed with synthetic traffic data provided by BR&TE.

The computer used for those simulations was a MacBook laptop with a processor Intel Core 2 Duo at 2.26 GHz, with 4 GB of RAM. According to Carnegie Mellon University (Moravec, 2009) and to specialized software (Geekbench, 2010), the processor's speed of this computer is 10,000 MIPS (Million of Instructions per Second).

5.1. Scenarios

The scenario simulated is based on Gran Canaria Extended TMA, which includes three STAR routes up to the runway and all the available Flight Levels. The modeled surface sized 275 × 330 km^2 and the maximum allowed altitude for the experiment was 12,800 m. The spatial resolution for the SDS was 100 m between discrete points.

```
ACT RTE   LEGS     1/3
 223°      0.9NM
TERTO        .790/FL300
 251°      92NM
WPT01        .790/FL300
 202°      51NM
TOD01        .790/FL300
 202°      41NM
WPT02         300/FL170
 262°      9.6NM
ENETA         300/FL138
RNP/ACTUAL-------------
2.00/0.02NM    RTE DATA>
```

Fig. 18. B738 FMS data.

```
  ACT RTE    DATA      1/3
              ETA       WIND
TERTO       1459z   000°/  0

WPT01       1511z   000°/  0

TOD01       1517z   000°/  0

WPT02       1523z

ENETA       1525z
----------------DATALINK
<LEGS               FAIL
```

Fig. 19. B738 FMS data (ETAs).

Fig. 20 shows the shape of the TMA, with 1 runway, 2 merging points and 3 entry points. Route corresponding to entry point A has been synthetically added to the real TMA in order to increment the complexity of the scenario (2 merging points complicates the synchronization of the traffic).

Two sets of convergent trajectories have been used as a workload for simulations. The first one, with 30 aircraft approximating to the airport in an interval of 1 h is called *rush hour*, and the second workload, with 35 aircraft, is named *saturation rush hour.*

5.2. CD metrics and requirements

In 1997 Isaacson and Erzberger published an article with details of a pairwise CD algorithm to manage the US airspace (Isaacson and Erzberger, 1997). They found four necessary requirements for a CD algorithm: *efficiency*, *flexibility*, *completeness* and *trial planning capability*.

Efficiency was found the most influential factor in the design of a CD algorithm, since a CD module should be able to process a huge amount of trajectories in real time (it is know that pairwise algorithms have a quadratic complexity $O(n^2)$).

Flexibility is the ability to process the whole set of trajectories each time the track aircraft positions are updated (e.g., in case of deviations). Note they considered a processing-time of 10 s acceptable, as tracking radar had an update cycle of 12 s.

Completeness refers to the ability of the CD to detect all the existing conflicts among a set of trajectories, whilst not warning about false conflicts. It is more important for those algorithms that use probabilities (i.e. risk of deviation) to determine a conflict.

Trial planning is the automatic process of proposing a resolution. It will be ignored in this paper, since the process of proposing resolutions corresponds to the CR system.

5.3. CR metrics and requirements

In 2007, Farley, Kupfer and Erzberger (NASA) (Farley et al., 2007) proposed two metrics to analyze the performance of CR systems, trying to establish a formal frame to allow comparatives between different algorithms: the *safety* and the *efficiency*.

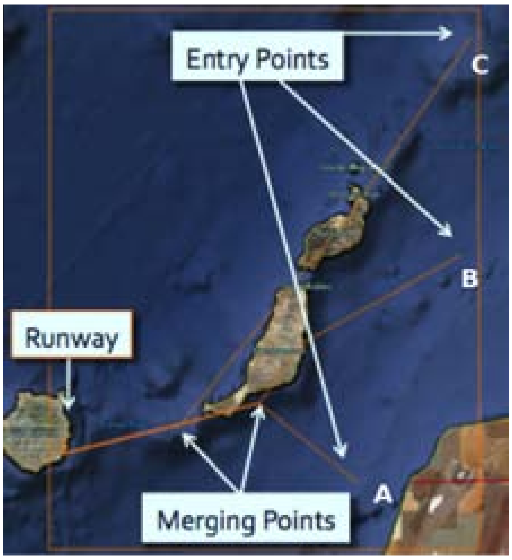


Fig. 20. TMA scenario.

Safety is a CR characteristic that is measured with the percentage of conflicts that have been correctly solved over the total number of detected conflicts.

Efficiency is defined by the average delay per solved conflict (the lower is the average delay, the higher is the efficiency).

In 2008, same authors published some studies about these metrics (Kupfer et al., 2008), concluding that both parameters are highly affected by the kind of scenario under consideration (so comparisons among different algorithms should be done under same scenarios and workloads). They also suggested the scientific community to develop new metrics to evaluate the quality of CR resolutions, and also to enable comparisons between different algorithms.

In this article the *runway utilization index* is proposed, ρ, as a metric of efficacy of a CR algorithm and allowing comparisons between resolution algorithms. This metric quantifies the percentage of *actual utilization* of a runway, λ, given a determined *service rate*, μ (Cooper, 1981; Balin and Erzberger, 1996; Bolender and Slater, 1996):

$$\rho = \frac{\text{actual utilization}}{\text{service rate}} = \frac{\lambda}{\mu} \tag{18}$$

According to NATS terminology (Cavanagh et al., 2008), the *actual utilization* of a runway, λ, is the number of observed aircraft landing in a certain time interval, *T*. Sometimes this concept is also called *landing rate* or *arrival rate*.

Actual utilization can be expressed as:

$$\lambda = \frac{T}{\tilde{t}_{cr}} \tag{19}$$

being $\tilde{t}_{cr}$ the *average temporal safety distance* achieved by CR for a given sequence of landings in a time period *T*.

The *service rate*, μ, is defined as the maximum throughput that is possible to obtain from a runway for a given landing sequence of an aircraft mix (generated for instance by an AMAN/DMAN) under a given set of conditions (meteorological conditions, runway's layout, availability of taxiways, availability of landside resources, etc.). Service rate is the maximum number of operations that a runway is able to support in a time interval *T* (usually 3600 s). Some studies refer to this concept as *achievable capacity*, *available capacity* and *maximum capacity* among others.

Service rate can be represented as:

$$\mu = \frac{T}{\tilde{t}_{\min}} \tag{20}$$

being $\tilde{t}_{\min}$ to be the *minimum temporal safety distance* that can be observed between all the landing aircraft, as statistical average, in a time interval *T* (i.e. considering the maximum saturation of the runway).

Thereby, mixing previous equations for a same time interval *T*, the utilization index can be expressed as follows:

$$\rho = \frac{\lambda}{\mu} = \frac{T/\tilde{t}_{cr}}{T/\tilde{t}_{min}} = \frac{\tilde{t}_{min}}{\tilde{t}_{cr}} \tag{21}$$

Note that always should be $\tilde{t}_{\min} \leqslant \tilde{t}_{cr}$ (if not, CR would be generating trajectories with conflicts). Therefore, $\rho \in [0, 1]$, being 1 the maximum utilization of the runway (i.e. using the whole available capacity/service rate), and 0 the contrary. To achieve

$\rho = 1$ in a rush hour the CR system has to saturate the runway with minimum gaps between landings (corresponding to minimum safety distances). In presence of uncertainty, it would be not possible for CR algorithms to reach $\rho = 1$ because of the extra buffers required, but for CR benchmarking purposes ideal context operations can be considered.

5.4. Results and analysis of MTCD&R system

With 4 bytes per booking, the total size (in Gigabytes) of the SDS for the 30-aircraft scenario was 1.089 GB, whereas for the 35-aircraft scenario was 1.27 GB (a 2D projection of the SDS has been implemented in order to save RAM memory).

The MTCD&R system has been able to detect and solve the totality of the conflicts appeared in less than 1/2 s, including the generation of the output files encoding the final conflict-free trajectories, one file in *TXT* format (with UTM coordinates) and another one in *XML* (with WGS84 coordinates), which can be used to observe the motion of the resultant trajectories with specialized GIS software (Figs. 21 and 22).

According to the metrics presented in Section 5.2, the CD module can be classified as *efficient* due to its linear behavior, and *flexible* due to the ability of re-computing all the trajectories in less than 1/2 s (ideal for real-time applications). Note that the usage of simplified wake vortex modeling rather than complex high-fidelity fluid dynamics has positively contributed to the obtained excellent performance.

The degree of *completeness* of the CD has not been quantified in this research, but it is expected that with a good parameterization of the 4D tube containing the vortex (obtaining the parameters through studying high-fidelity vortex simulations) all the existing conflicts may be identified and only a low degree of false conflicts may be detected. Other sources of uncertainty should be also considered to perform the completeness analysis (e.g. TP errors, weather conditions, etc.).

To analyze the CR module it has been assumed that the service rate of the runway only depends on the safety distances between landings (although in real cases it can also depend on other factors, such as the runway and airport layouts or the availability of taxiways, among others). Only Heavy aircraft has been considered in this model, so the minimum safety distance in absence of meteorological perturbations is 120 s. Therefore, using (20) and considering a time-interval of 1 h (3600 s), the maximum service rate of the runway under such conditions is:

$$\mu = \frac{3600}{120} = 30 \text{ aircrafts/hour} \tag{22}$$

Note that it explains why the 30-aircraft scenario is considered a rush hour scenario (30 aircraft is the maximum achievable runway's throughput in 1 h).

CR system adds a buffer of 1 extra second to minimum safety distances, so most of the aircraft cross the runway's threshold with 121 s time-distance respect the previous aircraft (some airplanes might cross with 120 or 122 s due to discretization errors in trajectories). Thus, the number of landing operations achieved by CR (actual utilization) under ideal conditions and with no uncertainty, can be calculated with (19) as:

$$\lambda = \frac{3600}{121} = 29.75 \text{ aircrafts/hour} \tag{23}$$

Then, the utilization index, according to (21), is:

$$\rho = \frac{29.75}{30} = \frac{3600/120}{3600/121} = \frac{121}{120} = 0.9917 \tag{24}$$

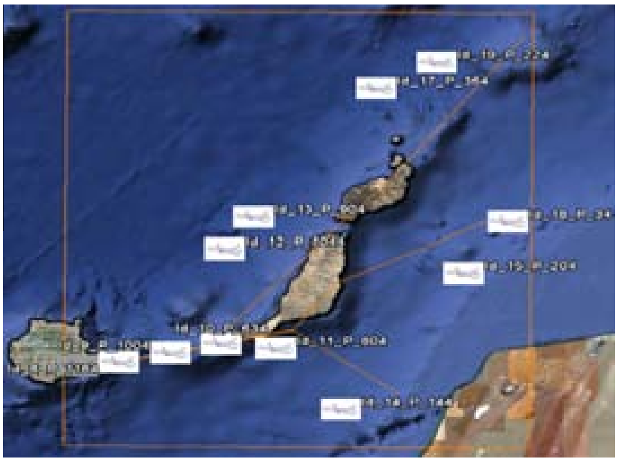


Fig. 21. CD&R simulation. 2D view.

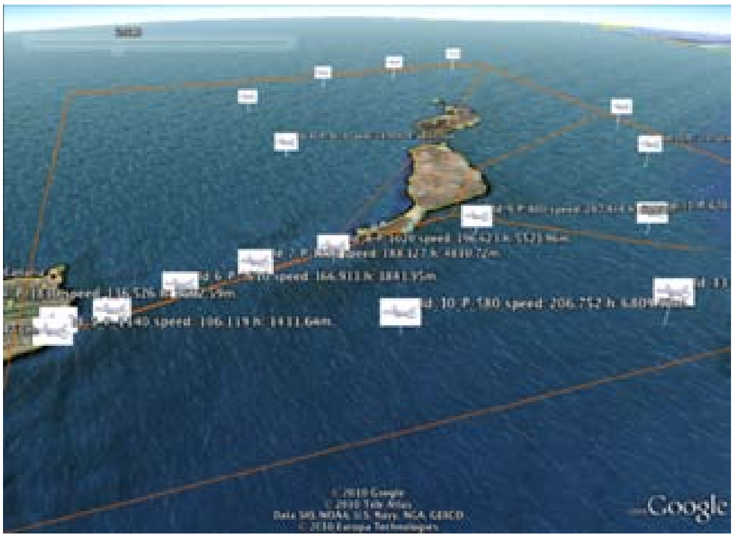


Fig. 22. CD&R simulation. 3D view.

What means that the MTCD&R generated trajectories use over a 99% of the whole runway capacity (considering a peak hour).

Table 3 shows the statistics generated by the MTCD&R system for the scenarios with 30 and 35 aircraft. Note that in both scenarios a utilization index (in bold) over the 99% has been achieved, implying (almost) the total exploitation of the available capacity.

It is also interesting to point out the big difference in total delays between both workloads, being 2099 s for the 30-aircraft scenario and 12,093 s for the 35-aircraft scenario. It explains why the 35-aircraft scenario was called *saturation rush hour*, and also allows making an idea of how difficult can become this scenario, which only adds 5 more aircraft, to controllers' workload.

MTCD&R outputs trajectories that accomplish with the requirements of being conflict-free (*safety*), minimize changes with respect the optimum RBT, and avoid the systematic use of holding procedures, so near-optimal consumption profiles can be expected (*fuel consumption and emissions efficiency*).

6. Perturbations and uncertainty

Despite all technological and management efforts developed in the SESAR framework, 4D RBTs are subject to different types of perturbations and uncertainties that can provoke some differences between the planned intended trajectories

Table 3
CD&R simulation results.

	Scenarios	
	30 aircraft	35 aircraft
No. of detected and solved conflicts	38	49
Average applied delay per aircraft	69.96 s	345.514 s
Average applied delay per conflict	55.23 s	246.796 s
Minimum applied delay	5 s	2 s
Maximum applied delay	125 s	666 s
Total sum of delays	2099 s	12,093 s
Total time of runway's utilization	3632 s	4242 s
Ideal time of runway's utilization	3600 s	4200 s
Utilization excess (total − ideal)	32 s	42 s
Index of runway's utilization, ρ	**0.991171**	**0.990051**
Aircraft/hour according to index	29.73	29.7015
Aircraft/hour ideal[a]	30	30
No. of landings with distance 120 s	3	3
No. of landings with distance 121 s	21	21
No. of landings with distance 122 s	5	10
Average distance between landings	121.069 s	121.206 s

[a] For the landing sequences considered in these scenarios.

and the actually flown trajectories. To preserve safety factors, it is important to consider how perturbations and uncertainties affect the MTCD&R algorithms in order to guarantee that the flyable trajectories will be conflict free:

Perturbations: refers to those external facts that affect the planned TMA schedules, such as cancelations, regulations, airspace blockings, ground delays and others. These kinds of fitful events justify the use of MTCD&R systems in the ATM, as a way to update the trajectory schedules taking into account the available information in order to predict the future state space within a look-ahead of 20–30 min. MTCD&R allows absorbing the effects of these perturbations in safety distances with a tactical planning, which ensure better efficiencies and safety than acting reactively to these perturbations.

Uncertainties: refers to those components of the system that are not properly represented with precision in the model and generate errors in the predictions, such as for example the weather conditions (specially wind), the aircraft control systems (both pilot and aircraft performance errors) and the positioning/tracking precision (even considering the more precise navigation systems). These sources of uncertainty, which are currently far away of allowing flying 4D trajectories in a precise way, need to be faced by adding extra buffers in the safety distances to compensate the lack of precision about the actual and future positions of the aircraft and vortexes, in a way that the current and future aircraft and vortexes locations can be identified with a required confidence at least within a certain time-spatial region. Note that the bigger is the uncertainty the bigger should be the used time–space buffers. However, by increasing the buffers, airspace latent capacity is also increased. So, precise uncertainty-buffers delimitation should be considered in MTCD&R algorithms.

The impact of these sources of uncertainties in the vortex model requires the use of extra buffers, i.e. increasing the radius of the 4D tube containing the vortexes and also increasing the time windows of the expected passing-time for all the waypoints. Taking into account that incoming navigation systems are expected to give a maximum tracking error of 185.2 m (RPN-RNAV 0.1NM), it has been considered that a radius of 300–400 m (150 m for wake vortex envelope plus 185.2 m due to tracking errors) should be enough to ensure safety for the most suitable weather conditions and considering large aircraft (largest vortexes).

Nevertheless, the radius parameter could be dynamically changed according to a precise weather prediction with a high updating frequency and according to the corresponding vortex category of each aircraft. Note that the capability of the MTCD&R algorithms to be executed in real-time (i.e. less than 1 s with a medium-power computer) is an important factor to tackle the uncertainty.

With regard to the temporal adjustment of the 4D trajectories, in this research it has been considered that the minimum temporal distances taken from ICAO documentation (120 s for Heavy aircraft) are conservative enough for the most suitable weather conditions and for all the wake vortex aircraft categories; thus, no extra temporal adjustment is required with regard to safety factors. However, the algorithms presented can also be set with dynamic parametrization for each vortex durability, opening the door to integrate the system with technological solutions that update the vortex durability information in real time, such as for example the LIDAR technology used as a real-time wake vortex sensor (Wiegele et al., 2008). A more precise parametrization of wake vortex durability would lead to a more efficient use of airspace capacity, while maintaining same levels of safety.

If for any unexpected reason a particular aircraft exits the uncertainty tube, then it is said to occur a *deviation* (i.e. it is considered that the aircraft is not following the expected nominal trajectory). When a *deviation* occurs it is necessary to update in the MTCD&R system the expected trajectory for this aircraft, and thus to take control actions to give the aircraft back to the original intended trajectory or to follow a new proposed trajectory taking into account the possible interactions with other trajectories (i.e. a *deviation* is managed as a particular class of *perturbation* as soon as it is detected).

The risk of *deviation* may be included in the algorithms presented in this paper by using different tubes whose radius increase with time (uncertainty grows with time) and with different probabilities associated, similarly to the methods used by current operational CD systems like iFACTS (Whysall, 1998), thus improving the efficiency and robustness of the CD&R algorithms. See Fig. 23. The ability of the algorithms to run in real-time would allow a continuous MTCD&R rolling process that may contribute to reduce the negative safety impacts of trajectory deviations in TMAs.

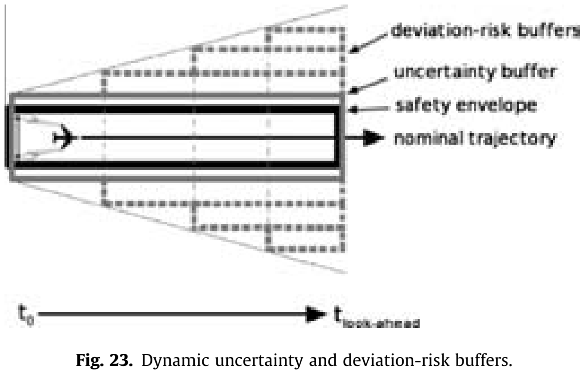


Fig. 23. Dynamic uncertainty and deviation-risk buffers.

7. Conclusions and outlook

One of the most important strategic challenges related with the deployment of the Single European Sky is the need of finding efficient ways for managing the available airspace capacity to ensure a sustainable air transportation system, especially in TMAs since they currently are the main bottleneck of the airspace system. Improving the decision support tools used to reduce the task-load of air traffic controllers and to improve the runways throughput is one of the ways to take better advantage of the airspace capacity.

In this paper, a CD and CR algorithm has been presented, integrated in a single MTCD&R system. Simulations with two different scenarios of heavy traffic entering to a TMA, *rush hour* (30 aircraft) and *saturation rush hour* (35 aircraft), has been used to show the excellent results of the implemented MTCD&R.

The CD algorithm has shown capabilities to work with wake vortex simplified models to perform the conflict detection using time-based distances and, at the same time, storing the state-space of the problem (like a 4D snapshot).

The excellent runtime performance of the CD module, due in part to the use of a non-pairwise (and SDS-based) CD algorithm, may enable the development of MTCD&R applications that provide in real-time with an updated feedback about the state-space. This feature could contribute to tackle the uncertainty related to the (expected) trajectories to be flown by aircraft.

The CR algorithm presented is based on vectorizations calculated to absorb the necessary delays to solve a conflict. The conflict-free trajectories have been calculated to minimize the change with respect the optimum reference (RBT), while taking into account the required 4D restrictions to solve the conflicts whilst maintaining at minimum the safety distances (efficient use of the available runway's capacity), as well as the computation of the Top of Descent for a CDA maneuver with a constant descent indicated air speed. Holding procedures were avoided by MTCD&R as they can imply strong fuel-consumption inefficiencies.

Flyability of these CR trajectories has been validated with real FMS avionics and with a certified B738 Full Flight Simulator. The proposed CR algorithm is still far away of considering resolutions for complex scenarios (i.e. considering arrivals, departures and cruise traffic mixed in the same TMA), however, it showed to be effective in relaxed scenarios and demonstrated good interaction with the SDS-based CD algorithm. Due to that, it can contribute as a baseline for the design of improved CR applications.

An *index of runway utilization* has been proposed as a new metric to measure the quality of MTCD&R outputs, as well as to enable comparisons between different systems. Analysis based on this metric (in absence of uncertainty) has also shown good results for the MTCD&R system.

Altogether, these results suggest that this MTCD&R system may contribute, as a baseline of a future Decision Support System platform, to improve the air traffic management, especially in congested TMAs, since it adapts to the requirements of the Single European Sky established by the SESAR programme, that is: it maintains or improves the *safety levels* of operations (all the conflicts were detected and solved), it augments the use of the latent *capacity* (by reducing controllers' task-load and maximizing the throughput of the runways), it gives *flexibility* to aircraft's planned trajectories (with 3D route dynamic allocation), and it reduces the *fuel-costs*, as well as the CO_2 *emissions* in the airport vicinities (by considering CDA operations and by avoiding holding procedures).

A technique based on 2D projections was used to reduce the memory requirements of the SDS but future work should be focused on reducing, even more, the growth in memory of the SDS. SDSs based on relational databases should be explored, since they might drastically reduce the memory growth.

The 4D snapshot provided by the SDS opens the door to explore the state-space of the problem. The integration of this MTCD&R system with Petri Nets that exploits the state space stored in the SDS could lead to find new CR algorithms that takes into account the network domino effects caused by the proposed resolution maneuvers, thus with potential for achieving better ATM global resolutions.

Finally, future research will also be addressed to analyze how the consideration of *uncertainty* in the models affects the MTCD&R algorithms as well as the index of runway utilization, and how to tackle this uncertainty in order to generate more robust conflict-free trajectories.

Acknowledgements

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7.2 *“Relational Time-Space Data Structure To Enable Strategic De-Confliction with a Global Scope in the Presence of a Large Number of 4D Trajectories”*

Article 2, “*Relational Time-Space Data Structure To Enable Strategic De-Confliction with a Global Scope in Presence of Large Number of 4D Trajectories*”, has been published in the Journal of Aerospace Operations. It presents two technological innovations applied to the SDS concept presented in previous paper in order to enable and set the usage for the strategic de-confliction of thousands of trajectories at the European airspace. One of the main shortcomings of the SDS presented in Article 1 was that it needed a lot of computer main memory, which made difficult the usage of the same SDS concept for wider airspace sectors and larger number of trajectories. In this paper the Relational SDS (RSDS) concept is presented, which modifies the internal logical architecture of the SDS (i.e., how the SDS allocates the bytes of memory to store the ATM information), and thus achieves reductions of more than 98% with respect the memory needs to store the same ATM information in the original SDS. A second concept, the Time-Spatial Data Structure (TSDS), has added the time in the structure of the SDS, which has represented an important qualitative shift of the concept and has notably improved the efficiency of the SDS during the processing of thousands of trajectories for strategic de-confliction purposes. Note that the problem presented in this paper (i.e., Strategic De-confliction) is different to the problems tackled in Article 1 (i.e., tactical time-based separations), thus the SDS configuration (i.e., which ATM information is stored and how) and methods used during conflict detection process must be also different.

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Relational time-space data structure to enable strategic de-confliction with a global scope in the presence of a large number of 4D trajectories

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Abstract. This paper introduces an innovative framework for the design and implementation of new ATM decision support tools for strategic de-confliction. The main key implementation aspects to support an efficient state space analysis of more than 4000 4D Trajectories in the entire European ATM is described. The paper focuses on the innovative aspects developed to improve Spatial Data Structures, i.e. the paper focuses on the new Relational Space Data Structures and Time-Space Data Structures concepts, that allow supporting strategic Conflict Detection (CD) between a large number of 4D trajectories and a wide airspace region. Results have been tested in the WP-E project STREAM, whose aim is to coordinate the entire European ATM traffic at strategic and tactical levels, thus requiring the processing of large number of trajectories under heavy traffic conditions. The new and efficient CD algorithms presented in this paper may contribute to increase airspace capacity in the SESAR framework for the period up to 2020.

Keywords: Trajectory based operations, 4D trajectories, strategic de-confliction, spatial data structure, dynamic route allocation, air traffic management

1. Introduction

One of the most important challenges of SESAR with respect the current ATM is the introduction of the Trajectory Based Operations (TBOs), which implies the use of 4D gate-to-gate precision trajectories (trajectories defined in the 3 spatial dimensions together with a time-stamp), also known as Business Trajectories (BT) in the SESAR's terminology for civil flights. The BT evolves out of a collaborative layered planning process, through which it progresses from the form of Shared Business Trajectory (SBT), which is shared for planning and negotiation purposes with all the involved stakeholders, to the Reference Business Trajectory (RBT), which is instantiated few minutes before the flight execution, representing the trajectory which the Airspace User agrees to fly and the Air Navigation Service Providers (ANSPs) and Airports agree to facilitate [1, 2].

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The term *strategic de-confliction*, is a new concept used in SESAR referring to actions taken by Network Manager (NM) to minimize the amount of conflicts (i.e. loss of due separation between two aircraft [3]) either prior to flight execution, when the takeoff time is known with sufficient accuracy (e.g. after push-back), or when the flight is airborne, but always with sufficient time to allow a Collaborative Decision Making (i.e. Collaborative Flight Planning) process to occur. It excludes tactical instructions and clearances that need an immediate response, but includes activities such as dynamic route allocation [25].

One of the goal of the SESAR concept is to deploy tools to assist the controller with complex situations and to reduce complexity by strategic deconfliction measures where necessary to increase capacity (extra capacity is required since an increment of the current air traffic levels in a factor of x2 is forecasted by 2030 [12, 13]). In this context, the introduction of automation support to conflict detection, situation monitoring and conflict resolution will be one of the principal changes for increasing airspace capacity in the period up to 2020.

Thus, strategic conflict management and traffic synchronization, would lead to pre-deconflicted 3D routes subject to dynamic refinement or adjustment during flight (i.e. 4D contracts). This constitutes a quantum leap with respect to the current airspace structure, which consists of a set of predefined airways depending on a ground-based infrastructure of navigation aids and relying on the subdivision of airspace into Air Traffic Control (ATC) sectors aimed at facilitating the management of flights. A progressive improvement in the accuracy of ground-based trajectory prediction through reduced flight uncertainty will lead to improved performance of controller support tools (greater accuracy and longer prediction horizons) and reduced controller task load per flight (fewer clearances with longer effective duration and increased dependence on the tools themselves to monitor compliance with the clearance and to check the progression of detected potential conflicts). In addition, because the data held and used by each sub region will be common, conflict prediction will be possible over a much longer timeframe and wider area than is currently possible.

The STREAM (*Strategic Trajectory de-confliction to Enable seamless Aircraft conflict Management*) project, launched within SESAR WP-E [http://www.hala-sesar.net/stream], aims at developing innovative computational-efficient Conflict Detection and Resolution (CD&R) algorithms for *strategic de-confliction* of thousands of trajectories within few seconds or minutes taking into consideration Airspace Users (AUs) preferences and network constraints. This is aimed at enabling traffic to be de-conflicted for wide airspace regions and permitting large look-ahead times of order of hours (e.g. two or three hours).

The principal scope for application is therefore represented by the (managed) European airspace, which falls under the responsibility of a single European Network Manager (NM) for what concerns the coordination and optimization of air traffic flows.

The strategic de-confliction STREAM algorithms can contribute to the achievement of NM's goals through the development of a proper traffic micro-model framework in which all the traffic at European airspace scale can be represented and managed as a (large) set of individual 4D business trajectories (i.e. micro-scale), and by suggesting strategically de-conflicted trajectories which closely match AUs preferred ones in a free-route environment, i.e. not constrained by pre-structured routes as occurring today. Note that this approach is congruent (and could contribute) to the INAP function ("Integrated Network management and ATC Planning") defined in the SESAR Concept of Operations Step 2 [37].

In order for the conflict resolution amendments to be effective, the complex interactions and emergent dynamics among trajectories must be taken into account with a global scope, since the resolution of a potential conflict may imply the reactive generation of a new set of conflicts in the network (i.e. domino effects). Due to the high degree of connectivity in the European ATM Network it is foreseen that only by considering at micro level the whole European Airspace (i.e. global scope), it can be ensured that all potential interactions are identified and that the final route allocation is globally de-conflicted under a collaborative optimization approach.

Spatial Data Structures (SDSs) have been explored under the STREAM project as a technique to implement the CD process, with excellent results in terms of time performance due to the linear computational complexity, O(n), of the CD algorithms based on SDS [18, 22]. The SDS capability to efficiently store spatial data (e.g. 4D trajectory information) at the time when the conflict detection among all SBTs/RBTs is performed, together with the efficient database access methods, have been a key factor for the development of new tools to analyze the entire ATM State-Space (SS) information under a global scope (a simplified 4D dynamic model is assumed in this paper, i.e. aircraft position and velocity at each time-step, so uncertainty and stochastic events are not considered in the traffic model). This enables for instance a complete and precise identification of the emergent dynamics that new trajectories may cause in the network (i.e. "domino effects") [17]. Causal models can be employed to provide with a strategically de-conflicted flight route allocation with a global scope, based on the SS information stored in the SDS since all the processed trajectories will remain stored as a "4D snapshot" of the ATM system [17, 33].

Original SDS-based CD algorithm [21, 22] presents some shortages in the scalability of the algorithm which invalidates it for STREAM purposes (i.e., to manage the 4D BTs of the whole European ATM coordinating the strategic and tactical phases of the conflict management by delivering a set of pre-deconflicted 3D routes). In this paper a new SDS-based CD algorithm is presented, which includes two innovations developed under STREAM, named:

- Relational SDS (RSDS): allows reducing the amount of Main Memory used by original SDS architecture approximately in a 98% whilst keeping the computational time performance (and the rest of the advantages) of the original algorithm. This massive memory reduction has been a key factor to enable the storage of the overall European ATM 4D state-space with a look-ahead time of several hours.
- Time-Space Data Structure (TSDS): adds a fourth dimension to the original concept of the SDS, which allows an efficient management of 4D data while considerably improves the run-time performance of the CD process when a large amount of trajectories is considered. The fast processing time achieved in the CD process might be an important contributor to efficiently adapt the ATM planning to uncertainties, perturbations and system disruptions, since the whole SS can be updated in real-time.

The design of these CD&R tools present good characteristics to ease the introduction of different sources of ATM uncertainty in the nominal models (e.g. by considering extensions for adding probabilistic information to the nominal models, or by achieving a fast update of the CD&R solutions in case of network changes). However, only a simplified ATM 4D nominal model will be considered in the results of this paper.

Section 2 includes the state of the art of the CD algorithms and the SDS concepts. Section 3 explains the technical and conceptual aspects applied to constitute the RSDS concept, while Section 4 introduces the technical and conceptual aspects of the TSDS. Section 5 gives details about how the RTSDS (i.e. RSDS + TSDS) has been configured for STREAM purposes, and how the CD process has been adapted and improved in consequence. A performance analysis including proof of algorithm linear complexity is included in Section 6. In Section 7 simulations and results are presented based on different academic and realistic (nominal) scenarios in order to confirm the advantages of the RTSDS, i.e. SS storage and high updating frequency. Section 8 reads the conclusions.

2. State of the art

2.1. Strategic conflict management

Conflict Detection (CD) and Conflict Resolution (CR) systems can be classified according to the way they handle detection/resolution when multiple conflicts among two or more trajectories materialize. When the algorithms sequentially detect and solve the conflict considering the minimum safety distances between each pair of trajectories without concern of other trajectories in the network they are based on a *pairwise strategy*, while they are based on a *global strategy* when the entire traffic situation is examined simultaneously [5].

CD&R processes for planning purposes are currently executed by Air Traffic Control Officers (ATCOs) only at a local airspace-sector level, with a look-ahead time typically limited to a maximum of 20 minutes (i.e. tactical applications) and with no global ATM perspective (i.e. pairwise) of how the decisions taken at local level affect the rest of the network. Some automated Medium Term CD (MTCD) tools have been developed to aid ATCOs during the tactical management of conflicts, e.g. FASTI, iFACTS, ERATO or VAFORIT, among others [6–9]. Early operational Automated CR tools are also focused on the tactical management of conflicts [9, 10].

A global CD&R perspective is required to strategically de-conflict the air traffic network. A resolution trajectory generated for solving a conflict between 2 trajectories could generate new interactions (i.e. *downstream or upstream conflicts*) that previously did not exist in the network. Also a resolution maneuver could solve original downstream/upstream conflicts that existed before in the original trajectory. These new interactions appearing in the network (or the elimination of pre-existing interactions) are called "domino effects" or more formally, *network effects* [26]. In [27] the authors underline the importance of taking into consideration these domino effects in the design of a CR system since these phenomena notably affect the quality of the resolutions from the network point of view, thus being a necessary condition for the adoption of an effective global strategy in the CD&R system, in order to provide optimal (or near-optimal) conflict-free network solutions. An interesting academic approach (i.e. non-operational) for en-route conflict resolution with global optimization by means of genetic algorithms was presented in [28].

The CD&R system proposed in STREAM project [29] takes into account a Collaborative Flight Planning approach. During the negotiation process Airspace Users may express their preferences according to their business targets (Free-Routing and 4D navigation capabilities are assumed), which will be used to find the most beneficial global solution (in absence of system disruptions and unforeseen big-impact network events) according to some commonly agreed metrics, thus formally realizing a multi-criteria global optimization of the –dynamically reconfigured– network route-structure. First, a pairwise strategy approach is followed, generating several *locally-optimal* (i.e. user-preferred) resolution trajectories per each detected conflict with no regarding of the potential emergent dynamics (i.e. "domino effects"). Later, a global strategy is applied through a causal model post-processing driven to determine several conflict-free network solutions, including the identification of the most preferred (i.e. *globally-optimal*) scenario. This is achieved through the causal analysis of the observed emergent dynamics (information obtained from the SDS) and by computing a global multi-criteria optimization function (e.g. efficiency, robustness, safety, equity, fairness . . .) commonly agreed between the NM and the AUs.

Uncertainty is a major topic affecting CD&R systems, especially when considering trajectories at strategic level [5]. A source of uncertainties comes from the limited accuracy of the positioning/tracking and navigation systems (even in most precise 4D navigation systems). These sources of uncertainty, which affect to the aircraft state (e.g., current position and velocity) are usually faced by adding extra buffers/tolerances in the safety distances in such a way that the current and future aircraft locations can be identified at certain time-spatial region with a required confidence interval.

Another source of uncertainty comes from Trajectory Predictor (TP) systems, which are used to project the states of the trajectories into the future, based on dynamic and aircraft performance models, in order to predict whether a conflict will occur. Unexpected trajectory deviations (i.e. aircraft crossing outside the allowed 4D uncertainty corridor) can occur, usually requiring an ATC action in case of tactical conflict management (e.g. MTCD systems). The uncertainty is near-zero at the last known position of the aircraft and increases with projected time ahead into the future (up to infinite). For strategic de-confliction purposes (e.g. STREAM), however, the uncertainty can be truncated to a maximum look-ahead time (e.g. 20 minutes) about its scheduled trajectory since it is presumed that tactical trajectory and conflict management tools (e.g. MTCD) will amend any trajectory deviation (if necessary) until the original trajectory is reached again. Similar concept was seen in [30]. In this paper a simplified 4D nominal dynamic model is presented, i.e. flight trajectories are assumed to be executed with no relevant uncertainties/deviations with respect the planning. Nevertheless, advanced probabilistic state-propagation model for a more realistic ATM representation, [4, 5, 15, 16] may be also supported with little impact in the design of the presented RTSDS (e.g. adding probabilistic information as a fifth SS dimension).

Finally, network disruptions are also an important source of uncertainty during strategic route allocation. According to [31] severe weather is identified as one of the factors currently most affecting the predictability of the network capacity and strategic flight planning. Other sources of uncertainties affecting the network capacity availability might be sudden military closed sectors, volcanic ash, wars, etcetera. These kinds of network perturbations in which capacity and demand can be drastically unbalanced require real-time algorithms to reconfigure the airspace while strategically de-conflicting the new allocation of routes.

A typical scenario at current European ATM with a planning horizon of 2–3 hours, is expected to include up to 5.000 flights active at the same time [29]. The high density and complexity of European air traffic implies a high number of interactions among the different trajectories, especially in those regions that are foreseen to be more congested. Conflict resolution with global optimization scope is considered an untreatable combinatorial problem (i.e. Non-Polynomial). Therefore the use of classical optimization techniques, analytical methods or exhaustive combinatorial exploration of the solution space, do not constitute practical methods to find conflict-free optimal solutions [28]. Thus a high computational efficiency in the STREAM strategic CD&R algorithms is required for analyzing and refreshing (updating) the state-space information of a several thousands of trajectories in real-time (i.e. in seconds or in few minutes), in order to dynamically adapt the airspace demand (i.e. flights) to the actual state of the ATM (i.e. available capacity) and ensure that, in presence of –probabilistic or nominal- conflicts among any SBTs/RBTs, the proposed local resolutions do not generate any secondary reactive conflicts on other zones of the network, while preserving flight efficiency and cost-effectiveness of flights as close to the optimum as possible.

2.2. SDS-based CD algorithms

A SDS (Spatial Data Structure) is a database that represents a spatial region (e.g., an air sector) by using individual memory positions to represent each of the discrete (3D) coordinates of the sector. Such memory positions are sorted in a way that, given a certain coordinate, the spatial information stored inside the SDS (associated with such a coordinate) is easily recoverable applying simple mathematical formulas [18]. The SDS can be conceptually represented as a mesh of discrete points distributed throughout the

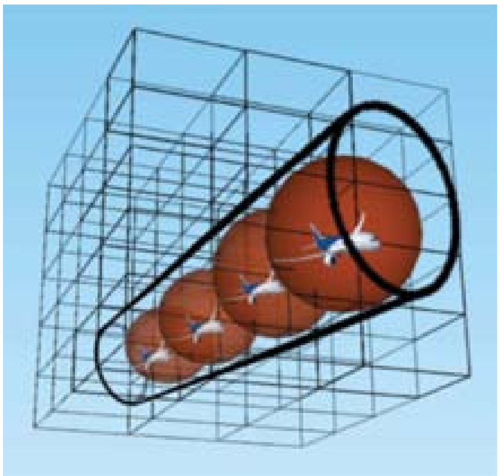


Fig. 1. SDS conceptual representation.

space region that is being considered by the conflict detection process, as shown in Fig. 1. Note that inside this three-dimensional SDS, i.e. the cube of the figure, a discretized 4D trajectory (different 3D positions of an aircraft in different discrete time steps) can be found.

SDSs facilitate the storage and efficient processing of *spatial data*, which might be composed of *spatial information* (e.g. a discrete representation of either the flight trajectory or its corresponding enveloping safety tube) and *non-spatial information* (e.g. the time-stamps of every discrete trajectory or tube samples, together with the flight identification number). A common way to deal with the non-spatial component of the spatial data is to store it explicitly in one or several fields in the same database record associated with the spatial information component (i.e. the occupied coordinate) of the desired item (e.g. a flight trajectory discrete sample) [32].

See Fig. 2 to observe an example of spatial data and a specific SDS configuration used (for MTCD purposes) in [18]. Since the discrete airspace coordinates are represented by each row/record and sorted in sequential order in the database, they can be easily accessed for writing/reading applying the following equation:

$$SDSrow(x,\ y,\ z) = x \cdot Y + y \cdot Z + z + 1 \tag{1}$$

being *SDSrow* the record position inside the database that stores the information of a particular coordinate (x, y, z), with $x \in [0\ , X - 1]$, $y \in [0\ , Y - 1]$ and $z \in [0\ , Z - 1]$, and being X, Y and Z the maximum number of discrete coordinates (i.e. the order) of each spatial dimension, respectively. Consider coordinate (0 , 0 , 2) that applied to Eq. (1) returns the record position 3 of the SDS (i.e. third row in Fig. 2). Note that the information stored in each record –of this particular SDS– is about the different reservations of usage that are expected from each aircraft/flight of the scenario under consideration. In the third record it can be found that aircraft with $id = 15$ is expected to make use of the coordinate $(0,\ 0,\ 2)$ in the time window from second 50 until second 170.

Note that Spatial Data Structures share some characteristics with other efficient data management techniques that are often used in software engineering, such as the *occupancy grids* (which in fact is a

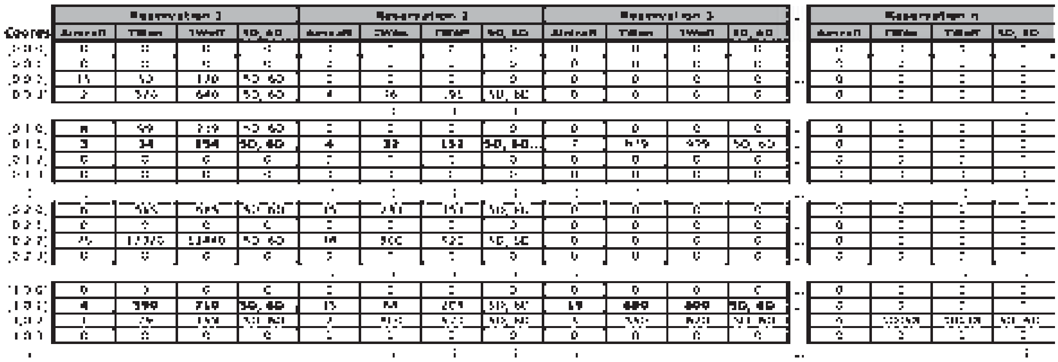


Fig. 2. SDS content example.

specialized usage of SDSs used in robotics to build in real time maps of the environment with probabilistic information for navigation purposes) [34], the *hash tables* (which are data structures to store keys/pointers –and only keys/pointers– to the data values of interest, but which are not necessarily related with any kind of spatial data) [35], or *look-up tables* (which are data structures to store pre-calculated values for a given function in order to avoid online –time consuming– calculations) [36].

The use of SDSs allows the storage of the entire State-Space description of the air traffic at a given time and its evolution over the time. All the processed trajectories will remain stored as a "4D snapshot" of the ATM system (higher dimensions can also be supported by adding extra 5D, 6D . . . nD information to each record; see Fig. 2), which makes the SDSs to be an interesting tool for CD&R purposes since:

- The CD process can be drastically speed up because the SDS acts like a powerful *spatial pruning* filter and in consequence a large number of trajectories within a large time-window look-ahead (e.g. 2 hours) can be processed by a CD module in few seconds, thus the air traffic state can be updated with a high frequency rate (which is beneficial to tackle some ATM sources of uncertainty).
- Causal models can be employed in the CR module to –efficiently– access and explore the SS information stored in the SDS, which enables the evaluation of all the potential network emergent dynamics (derived from the potential resolution trajectory amendments), thus improving the decision-making with a global optimization scope [17, 33].

Granularity or *resolution* of a SDS is the distance between discrete points of the SDS and –similarly to digital cameras– it determines both the "quality" of the SS stored and the "efficiency" at processing and managing the spatial data. Note that the excess of resolution may lead to a loss of computer performance as well as to an inoperable amount of memory requirements, whereas a lack of resolution may lead to lose some important objects of the space (thus missing the detection of some existing conflicts in the CD process, i.e. *false negative* errors). Factors as the size of the physical airspace to model, the size of the objects to be stored in the database, the speed at what these objects move, the quantity of memory available in the computer, and the speed of execution of the algorithms, among other factors, should be considered to determine the granularity of the SDS [18].

Spatial Data Structures are highly configurable and they allow to be set for its usage in different applications. SDSs have been explored under STREAM project as a technique to implement the strategic CD process, based on the excellent results obtained in collision avoidance algorithms (in videogames

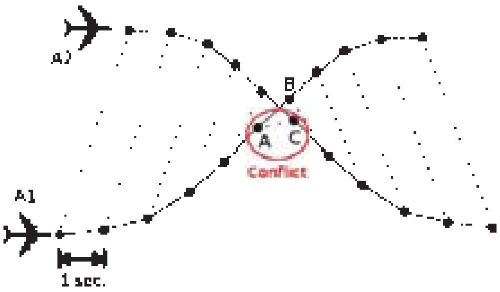


Fig. 3. Representation of a pairwise algorithm.

field) [22] and on a time-based MTCD prototype for Terminal Maneuvering Areas (aeronautical field) [18].

Following Sub-Sections summarize the main advantages and shortages of these two CD applications that use SDSs (i.e. collision avoidance and MTCD) that have been considered in STREAM during the design of the strategic de-confliction algorithms.

2.2.1. Collision avoidance based on SDS

Pairwise CD algorithms –with no filters applied– consist on distance calculations between each different pair of 4D trajectories, or more specifically, consist on distance calculations between the point-mass positions occupied by the aircraft at each given time-step. See Fig. 3 in which dotted lines indicate the 4D coordinates which belong to the same time instant.

It is well-know that pairwise algorithms have a computational complexity of quadratic order, $o(n^2)$, thus some kind of filters (e.g. flight level pre-filter, time-skipping strategies...) are often applied in operational applications (e.g. in [11]) in order to avoid some unnecessary comparisons and to improve in consequence the time performance of the algorithms.

In [21, 22], an efficient collision detection algorithm used in computer games field can be found, using a SDS as a powerful *spatial pruning* filter that linearizes the runtime/complexity, i.e. $o(n)$, of the collision avoidance algorithm. The algorithm uses the fact that collisions can only occur between agents that are geographically correlated, meaning that each *boid* (i.e. a mobile agent defining a trajectory) only can collide against another boid when both of them are at a certain short distance. This assumption allows reducing the amount of these pairwise computations among trajectories, by keeping the characters “pre-sorted” in the SDS, based on their location in space, in a way that it can be quickly found which of them are in a given neighborhood at a given time-step. Therefore, the detection of conflicts is performed for each boid by, first, identifying at each time step which are the *neighbors* (i.e. boids geographically correlated at close locations) in order to filter the amount of pairs to be compared with (i.e., *spatial prune* filter) and, later, checking the spatial distances among those still-remaining pairs of trajectories.

See Fig. 4 a boid is circled representing its safety area. The grid-cells overlapping with the circle (in dark color) represent the actual neighborhood for this boid at the time of simulation. Boids lying in the neighborhood at the same instant of simulation are candidates for a pairwise distance comparison. Note that figure represents a top-view of a 2D scenario, but similar concepts can be extended to 3D scenarios (e.g. a 3D-SDS might be needed for Free-Flight/Free-Route purposes in which current ATM standard Flight Level separation rules does not apply).

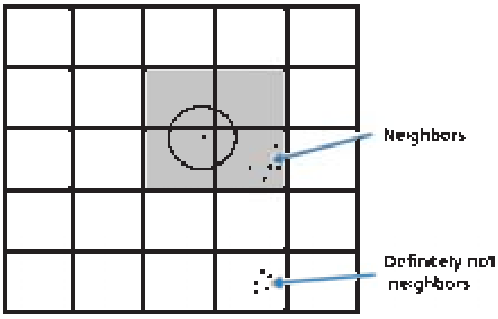


Fig. 4. Neighbors search to filter some of the pairwise comparisons.

In this algorithm, the SDS is configured to store only the *id* information of the boids that are located over the surface of the grid cells of the SDS (the bin-volume in case of a 3D scenario). There is no *time-stamp* information added to the spatial data stored in the SDS, since the content of the SDS is updated at each simulation time-step, when the next trajectory-position of the boids is determined (boid trajectories are not planned but computed online). If at current time of simulation a conflict/potential collision is detected, the boids *react* by changing their trajectories at next time of simulation. This reactive strategy works fairly well for collision avoidance in videogames. However, the emerging dynamics effect can make the avoidance of collisions unfeasible when a large amount of boids is considered. Thus, the whole algorithm and SDS architecture must be reconfigured for ATM planning applications, such as strategic de-confliction and/or tactical management of conflicts in the European airspace, in which a look-ahead planning horizon is required and domino effects must be considered, together with ATM uncertainties.

2.2.2. *MTCD based on SDS*

Regarding to the targets defined for the SESAR Service Level 5 [14], a MTCD algorithm for Terminal Maneuvering Area (TMA) that checks time-distance separations between approaching/landing aircraft according to the turbulences generated by other aircraft (wake vortex) has been described in [18]. The SDS is used in this algorithm to take a “4D snapshot” of the scenario in where the aircraft execute their trajectories and the vortexes are generated.

Figure 2 illustrates the logical architecture of SDS (filled with example data content) for this particular CD algorithm, which stores at each database record the reservations of resources (spatial discrete cells) booked by each aircraft/flight (according to their expected vortex dimensions). Note that a different SDS configuration is used in this algorithm: unlike above conflict avoidance algorithm in which each SDS record represented a grid area/volume (also called *bin*), in this MTCD algorithm every record of the SDS is treated as a single discrete coordinate, i.e. a spatial resource that only can be used by one aircraft at a given time (time window of utilization was considered and was fixed to 120 seconds for each flight wake vortex duration for simplification purposes [3, 18]).

To detect (time-based) conflicts using the SDS, at the moment of storing a surface tube-point according to its occupied coordinate the algorithm reads the first column; if its value is empty (i.e. equal to zero) it means that no other aircraft intend to use such a coordinate, so this spatial resource can be booked without conflict (e.g. in Fig. 2 aircraft #15 could freely reserve (0, 0, 2) since there was no previous reservation). If the first column is not empty, then the algorithm compares the time windows. If they overlap, then a conflict is detected and the CR system is informed (e.g. in coordinate (0, 1, 1) there is a conflict between aircraft #3 and #4 because their utilization time-windows overlap). If the time windows are not in conflict, it means that the coordinate might be booked in the following column without informing the CR (e.g. in coordinate aircraft #15 could make a reservation with no conflict with previous reservation of aircraft #6). In next columns applies sequentially the same procedure (e.g. coordinate $(1, 0, 1)$ was booked first by aircraft #4 and later by aircraft #15, with no conflict with previous reservation made by aircraft #4 since their utilization time-windows do not overlap; however, when a third aircraft #19 made a reservation for the same coordinate, a conflict was detected with #4, while the second aircraft #15 was still conflict-free).

Several simulations in Gran Canaria TMA validated with B738 avionics demonstrated the potential interest of SDSs as efficient spatial information managers (that provides with a 4D snapshot of the scenario evolution) for ATM planning purposes (for tactical planning, in this case). However, the initial SDS logical architecture (shown in Fig. 2) suffered of some shortages related with an inefficient management of the computer main memory that made impractical the utilization of SDSs for wide airspaces and/or large amount of trajectories, thus impractical for strategic European ATM dynamic planning.

3. Relational SDS for reducing the memory requirements

One of the most important shortages observed in above SDS-based CD algorithms was the immense growth rate of the memory required by the algorithm when the number of trajectories to be processed is increased [18]. This problem, given a certain amount of available main memory, drastically bounds the size of the modeled sector and/or the granularity/resolution of the SDS and/or the amount of trajectories that can be analyzed. Therefore, a more efficient use of the memory is desirable.

The logical SDS architecture illustrated in Fig. 2 is constituted by a total of $X \cdot Y \cdot Z$ database records (i.e. rows). The value of X, Y and Z is determined by the length (i.e. order) of each spatial dimension (i.e. $lengthX$, $lengthY$ and $lengthZ$) divided by the size of each grid cell or bin (i.e. SDS resolution). Each of the records is configured to store N potential reservations, which occupy B bytes each in the main memory ($B = 4$ bytes in the MTCD application above). Thus, the total amount of memory required to allocate this SDS architecture is:

$$total\ Memory\ SDS = X{\cdot}Y{\cdot}Z{\cdot}B{\cdot}N = \frac{lengthX}{sizeBinsX} \cdot \frac{lengthY}{sizeBinsY} \cdot \frac{lengthZ}{sizeBinsZ} \cdot B{\cdot}N \tag{2}$$

Note that each time a new trajectory is added to the problem, the SDS increases its memory positions (of size B each) in an amount equal to the number of rows required to represent the airspace scenario of interest. This usually means a huge amount of new memory positions due to the airspace sizes needed for ATM applications. Also note that the amount of required memory grows cubically with the three-dimensional granularity, i.e. reducing the size of the bins in a factor of 10 in each spatial dimension implies a memory growth of order 10^3. This fact makes often impractical the allocation of SDS in main memory of current commercial computers when a realistic ATM scenario is considered. In addition, the SDS architecture of Fig. 2 also limited the possibility of considering aircraft using a same coordinate more than once (for example during holding trajectories), since only 1 reservation per aircraft at each SDS record was allowed [18].

In general, the set of coordinates constituting the modeled airspace (i.e. rows/records of the SDS) is much greater than the set of coordinates used/reserved by all the aircraft. When it happens (it should be true for ATM applications), it bring as a consequence that most of the memory positions of the SDS are not being used to store any kind of useful information (i.e. lot of SDS reservation fields are set to zero), whereas the amount of memory required for a potential reservation of any coordinate/record has been

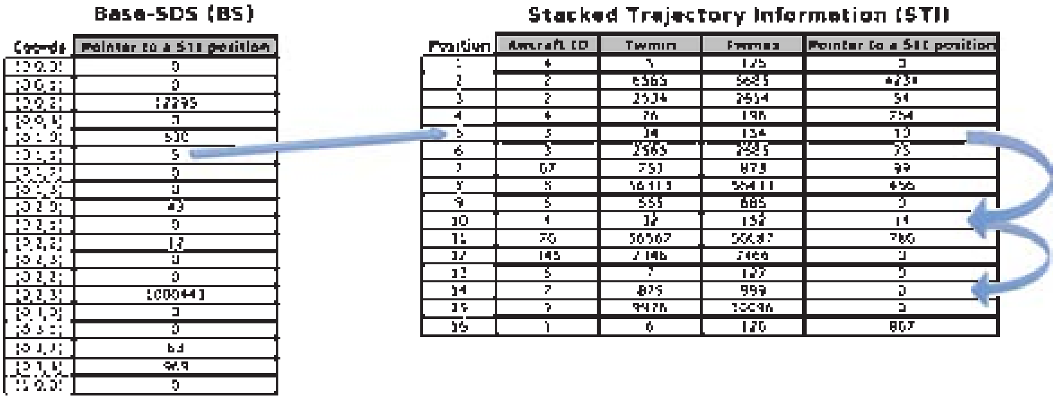


Fig. 5. Relational SDS architecture.

already allocated (see empty record in Fig. 2). A more efficient way to manage the information, thus minimizing the immense memory growth of the SDS, can be achieved by creating different databases, one optimized to store the basic structure of the SDS (i.e., creating the memory positions that models the airspace that will be used to efficiently manage the spatial data), and another one optimized to store the non-spatial information of the trajectories/reservations. The content information of those databases can relate each other like in relational databases, i.e. through database keys/pointers to outside database records.

To implement a Relational SDS (RSDS) with the equivalent functionality of the SDS seen in Fig. 2, two different databases are required (see Fig. 5). The Base SDS (BS) is a database built with the same amount of records than in Fig. 2 (i.e. with one row for each discrete coordinate of the airspace), but with only 1 field/column per record (usually occupying 4 bytes) instead of N fields/columns for N trajectories ($4 \cdot N$ bytes). The content of this unique column may be zero or may store a pointer to a record position of the second database.

The second database, named Stacked Trajectory Information (STI) in Fig. 5, will store all the coordinates going to be used by all the trajectories. The particularity of this database is that it stores all the information about trajectories in a stack (i.e. FIFO order), which allows optimizing the storage of the information since no empty records/memory-positions are present at this database (saving lot of memory with respect the non-relational SDS).

The structure of the STI is in general configurable regarding the requirements of the CD and CR algorithms (i.e. n-dimensional state space information can be stored), but always requires a column used to –potentially– store a pointer to another STI position (set to zero if no pointer is stored). In the example shown in Fig. 5 the STI consist of 4 columns: 3 of them used to store the non-spatial information of a booking, just containing the same information as in the non-relational SDS of Fig. 2 (in this case the *id* of the aircraft, the *time window begin* and the *time window end*). The 4th column allows storing a pointer to another STI position, if later reservations are made by same or different trajectories for the same coordinate.

As an example, note that same spatial and non-spatial information is stored in the SDS of Fig. 2 and in the RSDS of Fig. 5 with regards to the reservations made over the coordinate (0,1,1). If the pointer to STI is not zero (as in Fig. 5), it means that at least one booking was done for this coordinate. The value of the pointer indicates the position of the STI where the previous booking is stored (in the example, for coordinate (0,1,1) a pointer is stored to position 5 of STI). By accessing this record/row in the STI, it is possible to check if there is a conflict between the current and the previous booking (by checking if their utilization time-windows overlap). Once determined whether there is a conflict with such a previous booking, the fourth column of the STI current position is checked to search if another pointer to STI is present. If the pointer is set to zero, it means that no more previous booking for such a coordinate exists, so the current booking can be stored in the last free position of the STI (FIFO order) and a key/pointer to that record is stored in the fourth column of the actual current record of the STI. If the pointer is not zero, it sequentially proceeds with the same algorithm until a free position is found to complete the booking (in the example, positions 10 and 14 are sequentially checked).

The main advantage of the RSDS design is that the amount of memory required for the construction of the BS is mostly related with the size of the airspace sector to model and the desired granularity, thus its size does not increase with the amount of trajectories considered in the problem:

$$\mathit{total\ Memory\ BS} = X{\cdot}Y{\cdot}Z{\cdot}P = \frac{lengthX}{sizeBinsX}\cdot\frac{lengthY}{sizeBinsY}\cdot\frac{lengthZ}{sizeBinsZ}{\cdot}P \tag{3}$$

being P the amount of bytes required to store a pointer to a record (typically $P = 4$ or $P = 8$) and the rest of the parameters with the same meaning as in Eq. 2.

On the other hand, the amount of memory needed for the STI is calculated by:

$$\mathit{total\ Memory\ STI} = N{\cdot}L\cdot(B + P) \tag{4}$$

being N the number of trajectories to be processed, L the average amount of time-steps per trajectory and B and P with the same meaning as in Eq. 2 and Eq. 3. Therefore, the total memory space needed to store the STI when N increase grows with a constant linear rate much lower than in the case of the original logical SDS architecture shown in Fig. 2.

According to calculations made for several RSDS configurations adapted to different ATM scenarios, the memory management improvement presented here has implied important reductions in the quantity of used main memory, needing about a 95–99% less memory (in most ATM practical cases) than using non-relational SDS for the same scenario.

The state space of the problem is still available in the RSDS, like a 4D snapshot (or nD snapshot) of the ATM, thus being possible to extract and summarize useful information about the state-space as feed for new CR algorithms that may take advantage of the state-space exploration in order to find efficient and optimal conflict-free trajectories. CR algorithms based on Coloured Petri Nets has been able to explore the state-space generated by the RSDS with excellent results [23, 33].

4. Time-space data structures

The kind of SDS introduced in Section 2.2.1 for collision avoidance presents the ability of storing the information of the trajectories according to the grid cells/bins they occupy at a given instant of simulation, information that can be used as a spatial pruning filter to reduce the amount of pairwise comparisons during the CD process. For ATM planning purposes a similar CD algorithm could be used, refreshing the SDS at each time of simulation and filling a registry with the detected conflicts to be solved by a CR module. However, a historical record of the evolution of all trajectories over the time (like a 4D snapshot) is highly beneficial to provide a network overall view of the users' flight intentions and thus to generate information about potential emergent dynamics in an efficient way.

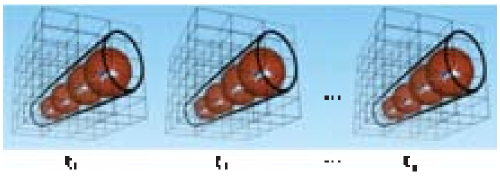


Fig. 6. TSDS conceptual representation.

A potential option to generate the 4D ATM picture could be to reconfigure the SDS to store at each cell/bin reservation the expected time-windows of utilization, in a similar way than seen in Fig. 2. Nevertheless, when the amount of trajectories willing to use same SDS cells/bins is considerably large (e.g. in most demanded European ATM sectors), even in different instants of time, the benefits of using such SDS configuration decrease. It is due to the fact that making comparisons with previous trajectories has a computational cost, even if filtered by the time-window of utilization.

By adding the 4th dimension to the structure of the SDS, i.e. the temporal dimension, it is possible to reduce the cost of comparing with previous trajectories, since reservations made for same spatial resources but for different expected times of utilization are treated as reservations for different time-space regions. Thus, the reduction of the pairwise comparisons is done by time-spatial queries, which is more powerful filter than only using spatial queries (see performance analysis in Section 6).

The resulting data structure configuration is named Time-Space Data Structure (TSDS). Conceptually, a TSDS can be thought as a set of T different SDSs, one for each discrete portion of time (see Fig. 6). Note that the discrete *portions* of time must not necessarily be time-instants, since time-windows could be also supported (for instance, Fig. 6 is showing a set of T different SDSs, each one storing 4 time-steps of different 4D trajectories executed in different time-windows).

The order of the temporal dimension (i.e. length of t axis) and the amount of discrete portions of time (i.e. size of cells/bins in the temporal dimension) define the granularity of the temporal dimension (i.e. $\frac{lengthT}{sizeBinsT}$), thus requiring the following amount of memory to store the TSDS:

$$totalMemorySDS = X{\cdot}Y{\cdot}Z{\cdot}T{\cdot}B{\cdot}N = \frac{lengthX}{sizeBinsX} \cdot \frac{lengthY}{sizeBinsY} \cdot \frac{lengthZ}{sizeBinsZ} \cdot \frac{lengthT}{sizeBinsT} {\cdot} B{\cdot}N \quad (5)$$

The meaning of parameters in Eq. 5 is the same as in Eq. 2. The combination of the concepts of the RSDS and TSDS is also possible (RTSDS), thus reducing the memory needs to support the TSDS (similar to Eq. 3):

$$totalMemoryBS = X{\cdot}Y{\cdot}Z{\cdot}T{\cdot}P = \frac{lengthX}{sizeBinsX} \cdot \frac{lengthY}{sizeBinsY} \cdot \frac{lengthZ}{sizeBinsZ} \cdot \frac{lengthT}{sizeBinsT} {\cdot} P \quad (6)$$

In the logical structure of the TSDS each 4D coordinate is represented by a single database record/row, sorted sequentially to ease the reading/writing content access. In [18] the access method to records of a (3D) SDS is presented; here it is extended to take into account the 4th dimension:

$$SDSpos = x \cdot Y \cdot Z \cdot T + y \cdot Z \cdot T + z \cdot T + t \quad (7)$$

Where SDSpos is an univocal record/row position inside the TSDS that stores the information relative to the given 4D coordinate (x,y,z,t), and X, Y, Z and T are the total amount of different discrete values that the variables x, y, z, t of a certain 4D coordinate can adopt, according to the order/size of each respective dimension.

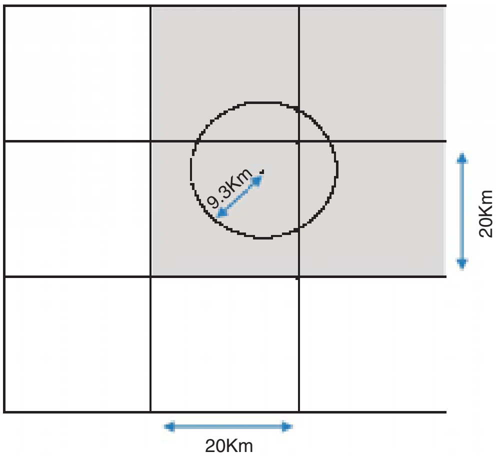


Fig. 7. Neighborhood (shadowed) defined by geometrical arguments.

5. RTSDS in CD&R to support strategic deconfliction

In order to build a strategic CD&R tool for the STREAM project it has been tested the following configuration using the above concepts of RTSDS (only en-route phase of flight is considered): the size of the bins (i.e. granularity) of the RTSDS has been set to 20 Km × 20 Km × 600 m. These dimensions are approximately the double of the minimum safety en-route separation defined in the current ATM [3]: 5NM (∼9.3 Km) in the horizontal plane and 1000 ft (∼300 m) in the vertical plane (typical values). The temporal dimension has been set with a resolution of 1 second, since the second is the same time unit used to discretize the 4D trajectories of the aircraft and it eases the construction and manipulation of the RTSDS.

The definition of the RTSDS bin-size has been set considering a trade-off between the trajectory pruning benefits of the RTSDS (too big bins means a less powerful "trajectory pruning") and the amount of RTSDS –time consuming– accesses required for neighborhood queries (too small bins require searching for neighbors in more bins). As seen in Fig. 7, with a 20 Km × 20 Km bin-size in it, is geometrically ensured that only 4 bins of the horizontal plane have to be accessed to complete the neighbor search at each trajectory time-step, while the amount of pairwise comparisons will be considerable filtered due to the relatively narrow dimensions of the neighborhood (40 Km × 40 Km). Similarly occurs in the vertical plane using a bin-size of 600 m: only 2 bins need to be accessed to ensure the detection of any conflict (for purposes other than STREAM, i.e. en-route strategic de-confliction, this granularity configuration might be revised). In total, the algorithm checks $4 \times 2 = 8$ adjacent bins, looking for neighbors at each time-step of a given trajectory.

If a neighbor aircraft is found inside the neighborhood formed by these 8 bins (in the same time-instant, since TSDS neighborhoods are time-spatial regions), then a direct distance comparison between the –expected– point-mass positions of the 2 aircraft is performed to check if they are in conflict.

As an example of the memory requirements needed by a RTSDS, let consider an airspace sector of 5.000 × 5.000 Km^2 of surface (e.g. to cover most of the European ATM), with 20 flight levels (6000 m.), and let consider a strategic look ahead for conflict detection of 5 hours with temporal resolution of 1 second. Then, the memory size occupied by the BS is (consider 4 bytes per row):

$$X = Y = 5000Km/20Km = 250 \tag{8}$$

$$Z = 6000m/600m = 10 \tag{9}$$

$$T = 5h \cdot 3600s/h = 18000 \tag{10}$$

$$BS = X{\cdot}Y{\cdot}Z{\cdot}T \cdot 4 = 250 \cdot 250 \cdot 10 \cdot 18000 \cdot 4 = 45GB \tag{11}$$

Let consider a maximum of 30.000 different trajectories within the 5 hours look-ahead of the scenario, with average flight duration of 2 hours (and resolution of 1 second). Then, the STI will occupy (consider 8 bytes per row):

$$STI = N{\cdot}L \cdot 8 = 30000 \cdot 2 \cdot 3600 \cdot 8 = 1.8GB \tag{12}$$

In total the RTSDS required amount of memory for this relatively wide scenario would occupy less than 47GB, amount that could be supported by current commercial 64-bit computers in RAM main memory (instead of using external hard drives that are much slower at reading and writing the information). Therefore, this RTSDS configuration can support the storage of the ATM 4D state-space within the 5 hours strategic look-ahead (other state variables, such probabilities to model some uncertainties, could be also supported). A CR module (e.g. based on causal-models) can take advantage of this information to consider the potential emergent dynamics of the proposed resolution amendments. Since the RTSDS content (i.e. the ATM 4D picture) can be updated in order of seconds (see performance analysis in Section 6), it can be used to dynamically adapt the flight routes allocation in response to network changes, thus balancing in real time actual available airspace capacity and demand (see Section 7 of results).

Fig. 8 shows an example of RTSDS utilization. This example considers a simplified scenario in which the height and time dimensions are fixed in a constant value (i.e. $z = 1$ and $t = 1$). Five nominal trajectories (i.e. Tr1, Tr2, Tr3, Tr4 and Tr5) are considered to be moving within an airspace represented by 16 bins of $20 \times 20\,km^2$ size each. Since a RTSDS is used for CD purposes, each of the bins must be considered to be a different spatio-temporal resource, thus only an instant of time of the whole flight trajectories is represented in the example (i.e. $t = 1$). Note that aircraft are represented by a point-mass model surrounded by a circle (5NM radius) demarking their required safety distances that cannot be crossed by any other aircraft (or rather, any other point-mass representation).

Fig. 9 shows the RTSDS storing the spatio-temporal information of the scenario while Table 1 presents the distances between each point-mass aircraft representation. It is assumed the following order of processing data: Tr1, Tr2, Tr3, Tr4 and Tr5.

- When Tr1 is processed no conflict is detected since there still are no other trajectories in the scenario.
- When Tr2 is processed, there is still not a conflict since safety distance between Tr1 and Tr2 is preserved, i.e. greater than 5NM. However note that trajectories Tr1 and Tr2 do not need to be compared to determine whether they are in conflict (i.e. distance between them do not need to be calculated) because they are not in the same Neighborhood, i.e. in 4 closest bins with respect the point-mass, which in this case for Tr2 is formed by ($x = 2$, $y = 1$), ($x = 3$, $y = 1$), ($x = 2$, $y = 2$) and ($x = 3$, $y = 2$). Thus, Tr1 and Tr2 are mutually filtered during the CD process.

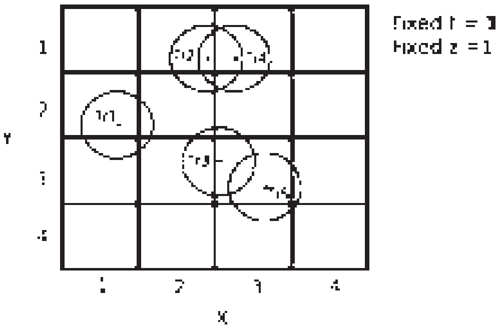
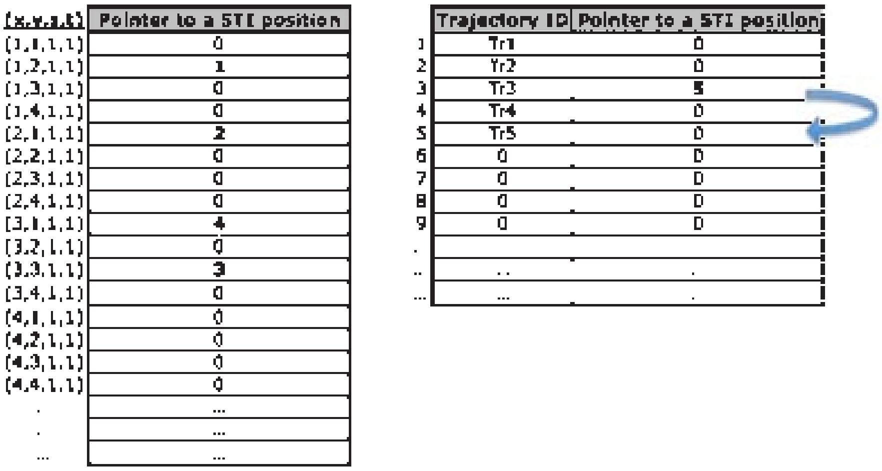


Fig. 8. RTSDS example scenario.



(x,y,z,t)	Pointer to a STI position
(1,1,1,1)	0
(1,2,1,1)	1
(1,3,1,1)	0
(1,4,1,1)	0
(2,1,1,1)	2
(2,2,1,1)	0
(2,3,1,1)	0
(2,4,1,1)	0
(3,1,1,1)	4
(3,2,1,1)	0
(3,3,1,1)	3
(3,4,1,1)	0
(4,1,1,1)	0
(4,2,1,1)	0
(4,3,1,1)	0
(4,4,1,1)	0
.	...
.	...
...	...

	Trajectory ID	Pointer to a STI position
1	Tr1	0
2	Tr2	0
3	Tr3	5
4	Tr4	0
5	Tr5	0
6	0	0
7	0	0
8	0	0
9	0	0
.		
..	..	.
...	...	.

Fig. 9. RTSDS example information content.

Table 1
Distances between trajectories

Distance (NM)	Tr1	Tr2	Tr3	Tr4	Tr5
Tr1	–	16	15	19	17.5
Tr2		–	15	**4**	21
Tr3			–	15	7.5
Tr4				–	20

- When Tr3 is processed, similar situation occurs, i.e. Tr3 looks for neighbors in its neighborhood composed by ($x = 2$, $y = 2$), ($x = 3$, $y = 2$), ($x = 3$, $y = 2$) and ($x = 3$, $y = 3$)), and there is no need for comparison since both Tr1 and Tr2 are filtered.

- When Tr4 is processed, Tr2 is found in its neighborhood, $(x = 2, y = 1)$, $(x = 3, y = 1)$, $(x = 2, y = 2)$ and $(x = 3, y = 2)$, and a distance computation is done thus detecting a conflict because the safety distance is lower than 5NM (i.e. their point-mass representation mutually crosses the safety circle of each other).
- When Tr5 is processed, a Neighbor Search is done in bins $(x = 3, y = 3)$, $(x = 4, y = 3)$, $(x = 3, y = 4)$ and $(x = 4, y = 4)$, where Tr3 is found as candidate for distance computation; no conflict is detected since distance is greater than 5NM. Note in Fig. 9 that the STI pointer of Tr5 has been stored in the second column of the STI of the Tr3 record, since Tr3 was processed first (see Section 3 about Relational SDS).

Note that only 2 distance computations were required to detect 1 conflict, instead of the $\frac{5\cdot(5-1)}{2} = 10$ required without the RTSDS filtering.

6. Performance analysis

6.1. Proof of linear temporal complexity

Let B the *total amount of bins* necessary to represent a given airspace of interest and N the *number of trajectories* coexisting/synchronized (i.e. worst case) in the scenario, and assume that all the bins have the same probability of being used by a given trajectory *at a given instant* (equiprobability is assumed for simplicity of the argument, but the proof is valid for any set of probabilities, including the ones associated to current ATM fixed route structure). Therefore, the probability p_B of an aircraft using a certain bin in a given instant is:

$$P_B = \frac{1}{B} \tag{13}$$

Thus, the *expected number of trajectories* found at certain bin, $\tilde{N}_B$, at a given instant is:

$$\tilde{N}_B = N \cdot p_B = \frac{N}{B} \tag{14}$$

Considering a neighborhood search like in Fig. 7 or Fig. 8 but in 3D version (8 accesses to RTSDS records are required), the *expected amount of pairwise comparisons*, K, is found with following equation:

$$K = 8 \cdot \tilde{N}_B = 8 \cdot \frac{N}{B} \tag{15}$$

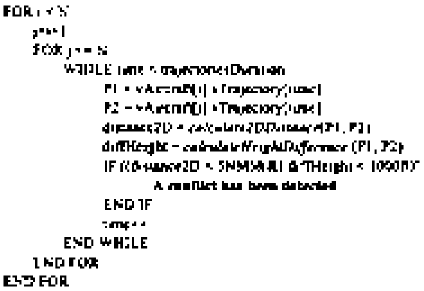
Usually $N \ll B$ (i.e. the amount of trajectories is much smaller than the amount of available bins in the airspace sector), so in general $K \approx 0$. Therefore, since each of the N trajectories will be compared at each time-step with K trajectories (i.e. neighbors), the temporal complexity of the RTSDS-based CD algorithm is linear, i.e. $O(N)$ (a constant amount of RTSDS accesses is required for each trajectory, e.g. 8 for a 3D space).

Similar proof can be stated for the SDS collision avoidance algorithm [22], however the RTSDS has the advantage of providing with a 4D/nD snapshot of the ATM at the end of the CD process.

Table 2
Performance Results

n	Pairwise T [ms]	RTSDS T [ms]
35	23	22
100	194	52
200	785	97
400	3153	213
500	4925	287
800	12620	579
1000	19738	837
1500	44447	1675
2000	79074	3200
3000	178008	6837
5000	493802	17513

ALGORITHM I. PAIRWISE CD ALGORITHM



```
FOR i < N
    j=i+1
    FOR j < N
        WHILE time < trajectoriesDuration
            P1 = vAircraft[i].Trajectory[time]
            P2 = vAircraft[j].Trajectory[time]
            distance2D = calculate2DDistance(P1, P2)
            diffHeight = calculateHeightDifference (P1, P2)
            IF (Distance2D < 5NM) && (diffHeight < 1000ft)
                A conflict has been detected
            END IF
            time++
        END WHILE
    END FOR
END FOR
```

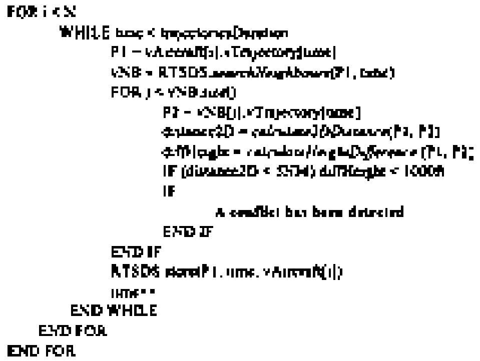
6.2. Empirical performance analysis

A set of different scenarios has been generated with the purpose of measuring the performance of the RTSDS algorithm. An airspace sector with dimensions of 400 × 400 Km^2 and maximum height of 30,000 feet has been considered.

Different traffic loads with 35, 100, 200, 400, 500, 800, 1000, 1500, 2000, 3000 and 5000 trajectories were generated with a random entry point located in one of the sides of the surface square and ending in a random exit position of the opposite side. All the trajectories last exactly 30 minutes, which results in an average ground speed of 450 knots and an average covered distance per trajectory of 417,6 Km. Fig. 10 shows a visual representation of the 100 trajectories scenario. Note that the airspace size considered is relatively small for the traffic loads considered, thus the performance evaluation is done under extreme traffic densities (worst case).

RTSDS acts as a spatio-temporal pairwise pruning filter during CD process (see Algorithm II). A comparison with a baseline pairwise CD algorithm, which does not use any type of SDS or prefilter (see Algorithm I), has been set in order to observe the gains in time-performance derived from the use of RTSDS. The measured performance of both algorithms is shown in Table 2 and in Fig. 11. Clearly,

ALGORITHM II. RTSDS-BASED PAIRWISE CD ALGORITHM



```
FOR i < N
        WHILE time < trajectoriesDuration
                P1 = vAircraft[i].vTrajectory[time]
                vNB = RTSDS.searchNeighbours(P1, time)
                FOR j < vNB.size()
                        P2 = vNB[j].vTrajectory[time]
                        distance2D = calculate2DDistance(P1, P2)
                        diffHeight = calculateHeightDifference (P1, P2);
                        IF (distance2D < 5NM) diffHeight < 1000ft
                        IF
                                A conflict has been detected
                        END IF
                END IF
                RTSDS.store(P1, time, vAircraft[i])
                time++
        END WHILE
    END FOR
END FOR
```

RTSDS.*searchNeighbours(P1, time):* search in 8 spatio-temporal bins of the RTSDS and returns vector vNB with all aircraft nearby *P1* at the given *time*. This function acts as sptaio-temporal pairwise pruning filter.

RTSDS.*store(P1, time):* allows the storage of the aircraft/trajectory identification into the RTSDS (e.g. for posterior CD or CR usage).

Fig. 10. Simulation Scenario (100 trajectories).

the use of RTSDS presents important advantages over the use of raw/non-filtered pairwise algorithms, presenting processing times up to 28 times faster in the case of 5000 concurrent trajectories. In addition, RTSDS is able to store the processed 4D information for a posterior state-space analysis (e.g. by a CR module). Also note that runtime linearity is empirically confirmed, even when in these sets of experiments extreme –and unrealistic– traffic densities have been considered.

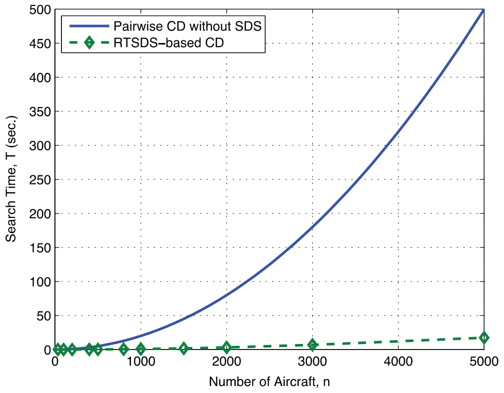


Fig. 11. Performance comparison.

7. Results

Two scenarios have been simulated: a) an scenario with 20 trajectories to illustrate the reliability of the conflict detection process based on RTSDS filtering, as well as the ability to store the state-space information of the ATM to find global conflict-free solutions considering emergent dynamics through causal models (e.g. Colored Petri Nets), and b) a peak-hour with realistic simulated trajectories flying over Europe (more than 4000 concurrent trajectories). No uncertainties were introduced in the nominal models.

In order to verify the reliability of the conflict detection process based on RTSDS usage, a scenario with 20 trajectories has been created and simulated with both the CD algorithm presented in this paper (the RTSDS version) and a software platform developed by NASA Ames: the FACET simulator. FACET allows performing several kinds of simulations related to the ATM, and it includes a conflict detection tool.

Figure 12 shows the 20 trajectories under consideration, with 10 conflicts detected among them by the SDS-based CD. Figure 13 shows the results of FACET simulation with CD tool enabled. It has been confirmed –by data inspection– that RTSDS-based algorithm detects exactly the same conflicts than the FACET tool; therefore the implementation of RTSDS is working properly as expected.

On the other hand, the RTSDS-based CD algorithm has been integrated with a CR based on causal models that analyzes the network interactions (i.e. domino effects) of different alternative trajectory amendments and finds several conflict-free network scenarios [17, 33].

The employed CR algorithm consists of two phases:

1. A Resolution Trajectory Generator (RTG) module that produces several alternative trajectories (i.e. resolution amendments) for each original trajectory in conflict (note that the original trajectories need to be processed by the CD in a first loop). These new trajectories are then sent back to the CD module to generate and store the necessary state-space information (i.e. secondary and tertiary conflicts).
2. An Interaction Causal Solver (ICS), specified in Colored Petri Net formalism [33], that analyses the interactions arisen among all the trajectories (original and alternatives) in order to find feasible combinations among them (i.e. conflict-free network scenarios).

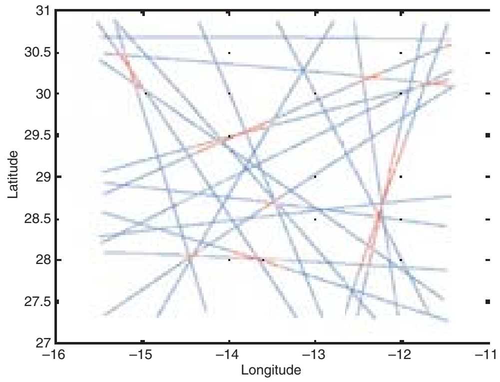


Fig. 12. RTSDS-based CD results for the 20 aircraft scenario.

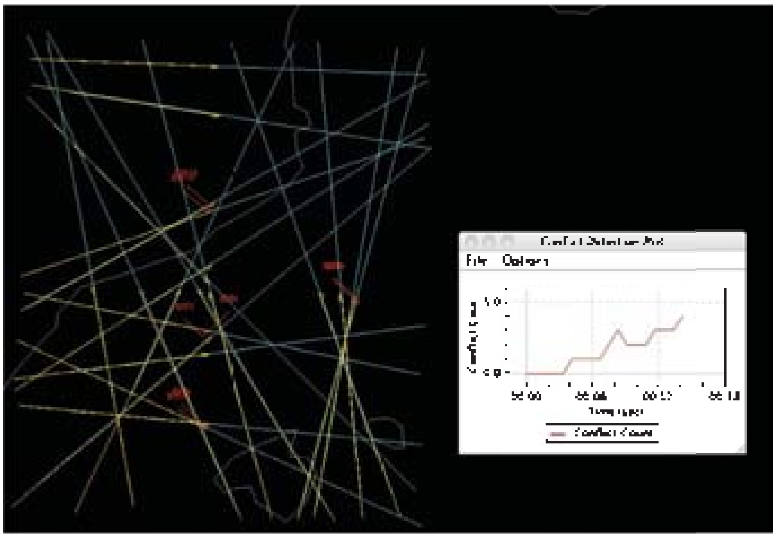


Fig. 13. FACET CD results for the 20 aircraft scenario.

Taking the same example above, with 20 aircraft/original trajectories and 10 conflicts among them, the RTG module has generated 54 extra trajectories, each one associated to an aircraft in conflict and solving (locally) at least one of the conflicts found by the CD. These resolution trajectories have been found based on a Geometric Optimization Approach [24], so they are (locally) "optimal" in the sense that it is minimized the change of the velocity vector with respect the original trajectories.

Fig. 14 shows a representation in FACET of the 74 trajectories (the 20 original and the 54 alternatives), which remain stored in the RTSDS after the CD process. These 74 trajectories generate 90 network interactions: the 10 original conflicts plus 80 new conflicts arisen with the introduction of the 54 new resolution trajectories.

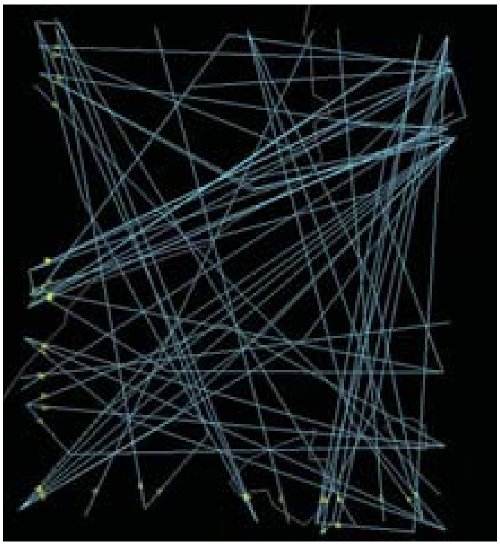


Fig. 14. FACET view of the original and alternative trajectories.

This information, which includes emergent dynamics at network level, has been sent to the ICS, which has performed a state-space analysis in order to find different combinations of conflict-free network scenarios. The causal model has been designed to pick at each iteration one of the possible alternative trajectories (original or amendment) associated to each aircraft and then “kill” those trajectories that are in conflict with those trajectories that have been already picked. Since the first trajectory assignation to an aircraft determines the set of trajectories available for the other aircraft, there exist different ways of finding conflict-free solutions by changing the order in which the aircraft are processed. This is a highly combinatorial problem that can be efficiently addressed with causal models [33]. At the end of the process the CR provided with several conflict-free trajectories.

Fig. 15 shows one of these conflict-free scenarios found by the CR module in which only 6 original trajectories has been changed by one of the “locally-optimal” resolution amendments to solve the 10 original conflicts among the 20 aircraft. Note that ICS module could take advantage of stabilizing domino effects (i.e. providing resolution amendment for one conflict indirectly solves other downstream or upstream conflicts). This solution has been also checked with FACET and no conflict was found, as shown in Fig. 16.

Finally, a realistic (nominal) ATM scenario with more than 4000 trajectories based on a yearly traffic peak day has been processed. Only the en-route phase of the flights were considered (i.e. from Top Of Climb up to Top Of Descent), with an average duration of 3600 s. Fig. 17 shows the trajectories over current fixed-route ATM structure, in blue, and the detected conflicts, in red. A total of 386 conflicts were detected among the original trajectories, results that were double-checked with Boeing R&TE simulation tools. The CD process was executed in less than 8 seconds, confirming the excellent performance results of the RTSDS that can contribute to the development of a dynamic strategic de-confliction and optimized route allocation system able to constantly adapt to ATM changes in real-time.

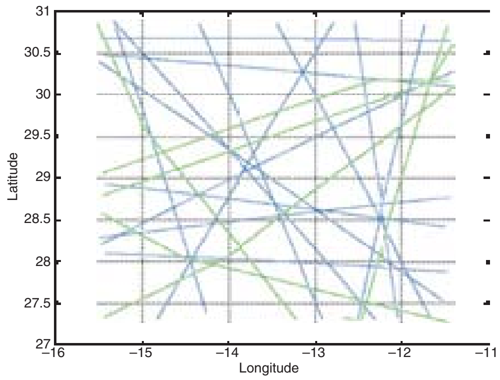


Fig. 15. CR solutions obtained from the RTSDS information.

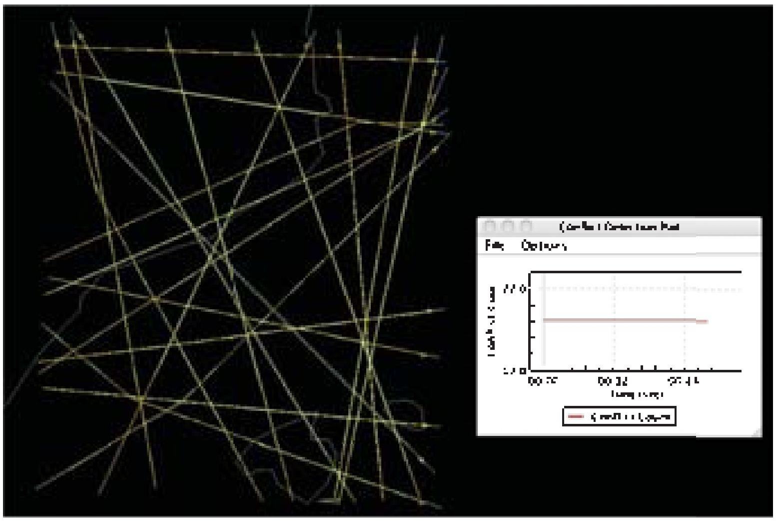


Fig. 16. FACET verification of the CR results.

8. Conclusions

STREAM project requires finding efficient conflict detection and resolution algorithms in order to process a large amount of trajectories in the European ATM for strategic de-confliction purposes, in alignment with SESAR 2020 and beyond ATM paradigm.

Spatial Data Structures have been previously explored in different CD applications (collision avoidance, MTCD), since they present the ability of storing the 4D trajectory information according to the spatial position they occupy within a certain space at a given time of simulation, allowing posterior spatial queries that reduce the amount of pairwise comparisons for detecting conflicts.

Fig. 17. 4000 trajectories over European ATM airspace.

Strategic CD algorithms may be also benefited of SDSs, since the efficient management of the ATM spatial data let the CD algorithms run at linear time (linear temporal complexity, O(n)), which represents an important enabler factor to process thousands of trajectories (including original flight plans and CR amendments) in question of seconds with a regular desktop computer (1000MIPS). The fast updating rate of the SDS content (i.e. ATM state-space) may contribute to the coordination and optimization of air traffic flows in response to network uncertainties (e.g. severe weather, runway incidents, trajectory deviations . . .), by dynamically suggesting de-conflicted trajectories in real-time (i.e. dynamic route allocation performed in question seconds or few minutes) that closely match Airspace Users preferences in a Free-Route environment.

Nevertheless, an important technological constraint of original SDSs impeding to be used for strategic CD purposes of STREAM was the immense growth rate of the memory requirements, which was a hitch to detect conflicts in large sectors (i.e. ECAC airspace), during long look-ahead times (i.e. several hours) and considering a large amount of 4D trajectories (i.e. several thousands).

An innovative technique called Relational SDS has been presented in this paper, which presents up to 95-99% reductions in the amount of memory required to allocate a SDS, thus overcoming the main shortage of the original SDS architecture that impeded its usage for strategic CD purposes in STREAM. Restrictions to model large airspaces, look-ahead times and number of trajectories are then softened, enabling the discrete 4D representation and storage of the European ATM system in the RSDS.

Another technique called Time-Space Data Structure has been also presented in this paper, which means a qualitative shift in the concept of SDSs by introducing a temporal dimension in the data structure that allows efficiently managing and storing the dynamic spatial information of the 4D trajectories for the CD&R purposes of STREAM (i.e. strategic de-confliction). Each record in the TSDS database means different spatio-temporal regions that are used as a powerful pruning filter to drastically reduce the amount of pairwise comparisons during the CD process, thus showing an excellent runtime performance that grows linearly, i.e. O(n), with the number of trajectories processed (either originals or CR trial amendments). The fast processing-time achieved in the CD process by using TSDS may contribute in uncertain scenarios to dynamically adapt the strategically de-conflicted scenarios to unexpected network changes (i.e. uncertainties) in in real-time.

Simulations with FACET software have confirmed the ability of the RTSDS-based CD algorithm to detect conflicts and to correctly identify the spatio-temporal conflict regions. On the other hand, the integration of the RTSDS-based CD algorithm with a CR module based on causal models has confirmed the importance of having the state-space of the processed trajectories stored in the RTSDS. Finally, a realistic ATM scenario with more than 4000 trajectories has been processed with excellent results confirming the potential contribution of RTSDS to strategic de-confliction algorithms.

More research is required to extend the benefits of using RTSDS for CD in STREAM, as for example to adapt the RTSDS to consider the curvature of the Earth when covering different time-zones (e.g., to cover the entire European ATM airspace), which may require adapting the SDS to work with geodesic coordinates. More research will be also produced using real traffic data to perform strategic de-confliction under the consideration of current European air traffic levels, such as for example introducing flight and network uncertainties in the models.

Acknowledgements

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7.3 “*Computational Efficient Conflict Detection and Resolution through Spatial Data Structures*”

Article 3, “*Computational Efficient Conflict Detection and Resolution through Spatial Data Structures*”, has been published in the International Conference on Research in Air Transportation (ICRAT). It highlights the importance of the SDS to keep stored a (pre-configured) ATM micro-model framework in which the complete 4D (or nD) representation of the ATM state (i.e., current state and its expected evolution over the time) can be efficiently stored and managed. Several applications of interest that use the available 4D information of that framework are presented, including the computation of temporal looseness among trajectories, the anticipation of emergent dynamics/domino effects, and the identification of network hot-spots. An empirical demonstration has been also included in order to show how the information available within the SDS can be used by a conflict resolution module (based on a causal model) in order to find global optimal solutions. Note that the scenario presented for the simulations is a congested tactical scenario (30-minute flight segments freely crossing an ATC sector), which was used as an intermediate step to the final European-level strategic deconfliction tool.

Computational Efficient Conflict Detection and Resolution through Spatial Data Structures

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Abstract— **The SESAR concept of operations establishes a new paradigm for the management of air traffic based on the concept of 4D Business Trajectory, which will be shared by the Airspace Users with all the relevant stakeholders prior to departure for planning purposes. This paper presents the conceptual and technological framework developed by the STREAM project, whose objective is to apply conflict detection and resolution algorithms on this Shared Business Trajectory, in order to deliver traffic to air traffic controllers already de-conflicted. This implies the need for computationally-efficient algorithms able to process a considerable quantity of trajectories within few seconds and to store enough information to ensure that the resolution of a primary conflict does not imply the creation of another one somewhere else in the network. Spatial Data Structures (SDS) constitute a perfect choice for this application, since they permit the conflict detection problem to be reduced to a linear complexity O(n) and provide a very natural representation of the status of the ATM system and of its evolution over time. The state-space information stored in the SDS by the conflict detection module makes it possible to run a conflict resolution algorithm to calculate the trajectory amendments, taking into account the network interactions and also allowing the extraction of individual and aggregated traffic information to improve tactical and strategic ATM decision-making.**

Keywords-component; 4D Trajectory, strategic conlict detection & resolution, spatial data structures, SESAR STREAM project.

I. INTRODUCTION

Currently, most Conflict Detection (CD) algorithms that are implemented in operational applications (CTAS, FASTI, iFACTS, ERATO or VAFORIT, among others) are mainly based on *pairwise strategies* [1–3]. Automated Conflict Resolution (CR) tools are currently under development, but early operational applications are also based on pairwise strategies [4, 5]. Unfortunately, it is well known that CD algorithms, when based on traditional pairwise strategies, have a temporal complexity of quadratic order, $O(n^2)$ [6]. This reduces their practical application to limited portions of airspace and traffic, due to the computational burden when trying to process thousands or tens of thousands trajectories. The number of trajectories currently using the European ATM every day is of the order of tens of thousands.

The STREAM project, a SESAR WP-E project in progress, aims at developing innovative computationally-efficient CD&CR algorithms that can process thousands of trajectories within few seconds. This will enable traffic to be de-conflicted for wider airspace regions and will permit longer look-ahead times than in current applications, thus contributing to fill the current gap between strategic and tactical planning in the ATM. The idea is to capitalize on the availability of the 4D trajectory information available prior to take-off, with the most accurate level of detail, according to the planning horizon, and based on the SESAR concept of operation [7]. The information on flight intentions and on the current and forecast status of the whole European network will be available through the Network Operations Plan (NOP), a continuously-updated rolling plan that could enable a seamless conflict management process running continuously from the strategic phase (pre-departure, collaborative design of the NOP) up to the execution one (automation-assisted, controller-driven conflict resolution).

Spatial Data Structures (SDS) have been explored under the STREAM project as a means to implement the concept, with excellent results in time performance due to the linear temporal complexity of the algorithms, O(n) [8].

In addition, the use of correctly-configured SDS allows the storage of the entire state-space description of the traffic at the time when the conflict detection analysis is performed, since all the processed trajectories may be stored as a “4D snapshot” of the ATM system.

This paper focuses on explaining the opportunities that SDSs could offer for the better understanding of the ATM and to make better decisions both at strategic and tactical levels of operation. The information that can be obtained from the state space stored in the SDS includes but is not limited to:

- **Analysis of interactions**: once the CR gets a set of conflicts detected by the CD, it can generate and propose different trajectory trials to solve a conflict. The SDS can be re-fed with these new trajectories in order to detect possible new conflicts (i.e. interactions) generated among the new trajectory proposals and the rest of the network. This ability has been initially validated with CR specified in Coloured Petri Nets formalism, giving promising results that are still not published.
- **Sensitivity analysis of departure-time changes**: most of the perturbations in the ATM occur prior

to departure [9], causing high uncertainty about the time of departure and generating new perturbations on the air-side (i.e. conflicts). By analysing the content of the SDS after processing the planned trajectories it is possible to quickly obtain relevant information about the temporal/longitudinal looseness of each trajectory. This analysis will contribute to generating useful information and practical constraints to make better operational decisions, by identifying which trajectories are more sensitive to changes and which ones generate more network effects if modified.

- **Network analysis**: it is of interest for the network manager (NM) to identify and validate the hot-spots with higher traffic densities and/or with higher probabilities of conflict, in order to plan and assign adequate resources in response.

This paper first contextualizes the findings by stating the targets and concept of operations of the STREAM project, within which the CD module has been developed. Afterwards, a summary of the main key features of the CD algorithm and the SDS is given to better understand how the state-space is generated and stored. Finally, there is a discussion of some of the opportunities that state-space storage opens. Conclusions and future research to be performed are also outlined.

II. STREAM CONCEPT OF OPERATIONS

The STREAM solution relies on one of the fundamental elements of the SESAR Target Concept: the 4D Business Trajectory [7]. It describes the intended trajectory in space and time for each flight and evolves out of a collaborative layered planning process through 3 sequential phases:

- the Business Development Trajectory (BDT), internal to the airspace user and not shared with the rest of the ATM community;
- the Shared Business Trajectory (SBT), shared for planning and negotiation purposes with all the involved stakeholders;
- the Reference Business Trajectory (RBT), which the Airspace User agrees to fly and the ANSPs and Airport agree to facilitate

The STREAM project investigates innovative algorithms that can make use of the information contained in the SBTs to perform conflict detection at pre-departure phase, thus allowing the integration of appropriate conflict resolution manoeuvres into the first RBT instantiation. It is foreseen that at pre-departure phase the agreement on the best trajectory amendments that provide conflict resolution can be reached through an iterative and collaborative process between Airspace Users and the Network Manager (NM). This should enhance the overall process of conflict management by closing the gap that exists at present between the long-term predictive part of the ATM system, represented by central flow management measures, and the short-term adaptive actions locally performed by tactical controllers.

A combination of different resolution strategies (route, speed and flight level modifications to the involved SBTs) can be applied to de-conflict the involved trajectories, depending on the characterization of the conflict (i.e. type, location, # of aircraft involved, etc.) and on the preferences of the Airspace Users. The computational efficiency of the algorithms running in linear time with respect to the number of trajectories considered, allows all European air traffic to be taken into account in order to ensure that resolutions of conflicts are effective. This means that traffic complexity can be maintained under control at local (ACC), regional (FAB) and even global (ECAC) levels and that resolutions do not generate secondary reactive conflicts on other zones of the network.

In order for the conflict resolution manoeuvres to be effective, the complex interactions among different traffic flows must be taken into account, since the resolution of one conflict may imply the reactive creation of a new one. Due to the high degree of connectivity in the European ATM Network it is foreseen that only by considering the whole ECAC Airspace can it be ensured that all potential interactions are identified.

The average daily number of flights in 2010 in Europe was around 26000 [12] with peak days of up to 36800 as on July 1st. Considering the typical distribution of take-offs in Europe, as showed in Figure 1 below, and taking into account that the average flight duration is 1h23' (according to [9]), it means that a two-hour sliding time window could be employed to filter insertion into the SDS, which will mean that there will easily be between 5000 and 6000 flights active at the same time. This number of flights will have to be managed in real time by the algorithms, thus imposing strong requirements on the computational efficiency of the algorithms employed.

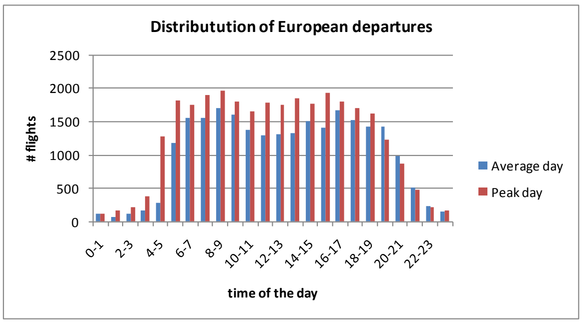


Figure 1: Daily distribution of take offs in Europe (Average day: 09/11/2010, Peak day: 01/07/2010). Source: EUROCONTROL ALL_FT data

The 4D trajectory information contained in the SBT will need to be padded with the uncertainty stemming from all the known affecting sources: airline and ground handling operations, airport constraints and availability of resources, status of the network and weather forecasts. It is foreseen that higher availability of information with better quality and reliability than today will be available in the future thanks to the System Wide Information Management (SWIM) concept [7]. The analysis of the most updated information available will allow the Network Manager in close cooperation with the Local Traffic Managers to build an "uncertainty tube" around each nominally predicted trajectory. This information will feed the CD&R system with a complete 4D representation of traffic in the network at European level for a look-ahead horizon of 2-3 hours. After processing all the 4D trajectories in the CD&R module the state space of the ATM system will be provided. Consequently it will be possible to:

a. Identify potential conflicts, likely violations of separation minima, i.e. two aircraft at the same level over the same geographical area at the same time.

b. Identify hot spots and congested areas.

c. Determine those trajectories that are more sensitive to becoming involved in a conflict in case of perturbations.

A set of possible resolution scenarios could be available for each conflict detected, each one weighted against several performance indicators for efficiency, robustness, fairness and equity [8]. In this case the tool will clearly indicate the different options that should be made available, together with the causative constraints. The AUs will have the possibility to express their preferences among different solutions to comply with the constraints, thus engaging in a sort of iterative negotiation process, in which the AUs communicate their preferences and the NM calculates the most preferred manoeuvres, associated with specific constraints.

Two main modalities are foreseen for embedding users' preferences into the conflict resolution process: either (i) Airspace Users attach a specific priority coefficient to each trajectory, in order for the NM to assess the individual impact of resolutions and to select and impose the best solution; or (ii) the NM communicates to the users the set of possible resolutions suggested by CR module and they in turn respond with the ranked order. The NM will then be able to select the preferred solution, i.e. the one whose sum of individual rankings is the higher. In a case where multiple solutions have the same score, the NM can apply a performance based rule to resolve ties.

A conflict can be detected either between different SBTs or between an SBT and an RBT already in execution. In this latter case there might be situations in which it could be more beneficial to modify an already agreed RBT than a number of different SBTs, even if this may require a greater coordination effort. In fact the change proposal should be triggered by the NM, channelled through the Flow Manager, to the Local Traffic Manager and then the RBT revision executed by the responsible ATCO.

Under all circumstances, final agreement between the involved service providers and the impacted Airspace Users will be necessary in order to close the SBT negotiation and to instantiate an RBT for each flight.

In the cases when the negotiation process does not converge to a feasible solution within a certain time limit, the ATM authority (i.e. the NM at the strategic phase or ATCO during the execution phase) will have the right to impose the most indicated conflict resolution measure.

The result of this process will be to have pre-synchronized traffic in the regions that are foreseen to be more congested. This synchronization will be agreed by involved actors (AUs, ANSPs and Airports) and formalized through the RBT, which will include the constraints in path and time derived from the strategic de-confliction measures.

Unexpected events could still occur requiring tactical interventions and explicit ATCO clearance will continue to be needed. However the overall predictability of the system will be enhanced, thus implying fewer tactical interventions and more stable plans.

III. SDS-BASED CD ALGORITHM

A. *Spatial Data Structures*

A Spatial Data Structure (SDS) is a database that represents a spatial region (i.e. an airspace or air sector) by using individual memory positions to represent each of the discrete (3D) coordinates of the sector. Such memory positions are sorted in a way that, given a certain coordinate, the information stored inside the SDS (associated with such a coordinate) is easily recoverable by applying simple mathematical formulas [12, 13].

For example, to find the information related to the trajectories using the coordinate (x,y,z) the following position of the SDS should be accessed:

$$SDSpos(x,y,z) = x*Y*Z + y*Z + z \qquad (1)$$

Where SDSpos is an univocal memory position inside the SDS that stores the information relative to the given 3D coordinate (x,y,z), and Y and Z are the total quantity of different discrete values that the variables x, y, z of a given 3D coordinate can adopt, according to the order (i.e. size) of each respective dimension.

Fig.2 shows a representation of the database, conceptually drawn as a table containing as many rows as there are discrete coordinates in the modelled airspace and as many columns as there are aircraft/trajectories to be processed (in this case, each reservation is composed by a set of 3 column-cells, and the each row is enabled to store *n* possible reservations, one for each of the *n* trajectories processed in the system).

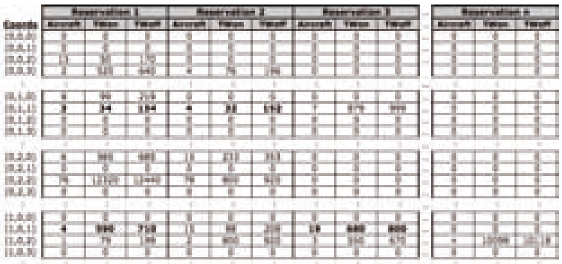


Figure 2. SDS representation as a database

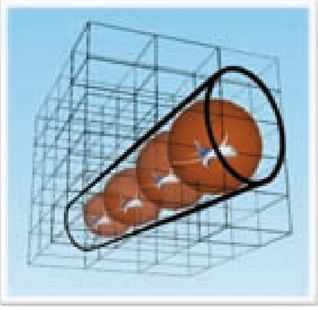


Figure 3. SDS conceptual representation

Fig. 3 shows a graphical conceptual representation of an SDS. In particular, the SDS can be thought of as a mesh of discrete points distributed throughout the space region that is being used in the conflict detection process. Note that inside this three-dimensional SDS (the cube represented in the figure) a discretized 4D trajectory is stored (different 3D positions of an aircraft in different discrete time steps).

SDSs are highly configurable and they can be configured for use in different applications. For instance, find in [8] two innovative techniques to improve the performance of SDSs, the Relational SDS (RSDS), which store the same amount of information but save around 98% of the required memory in comparison with the original SDS, and the Time-Spatial Data Structure (TSDS), which store the time-related information of 4D coordinates in the proper structure of the database, improving the performance for the conflict detection among 4D trajectories.

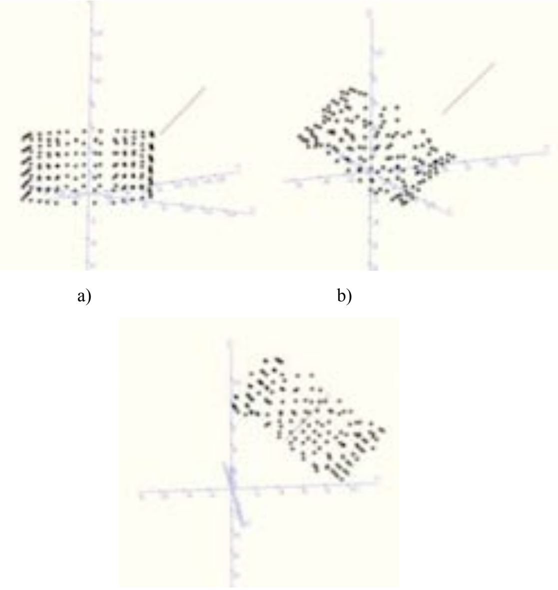
The *granularity* or *resolution* of an SDS is the distance between discrete points of the SDS. To determine the optimal separation between SDS points is not an easy matter, and there is no generic method for calculating it. Factors such as the size of the physical airspace to model, the size of the objects to be stored in the database, the speed at which these objects move, the quantity of memory available in the computer, and the speed of execution of the algorithms, among other factors, should be considered to determine the granularity of the SDS [12, 13]. Note that an excess of resolution may lead to a loss of computer performance or even to inoperable memory requirements, whereas a lack of resolution may cause the loss of significant objects of the space.

B. *Conflict Detection using SDS*

Two different ways of performing conflict detection with an SDS have been tested: first, by using discrete 4D tubes as safety envelopes for aircrafts in order to check overlaps among them, and second, by clustering the airspace in order to perform pairwise distance comparisons among a reduced set of trajectories [8]. As the purpose of this paper is to argue the advantages of having stored the state space of the ATM, only the SDS configured for conflict detection with 4D tubes will be presented, since this technique generates a richer and easier-to-access state-space than a configuration which clusters the airspace to reduce the number of pairwise comparisons.

The idea behind storing the state space is similar to taking a "4D snapshot" of the scenario in which the aircraft execute their trajectories. Note that in a particular algorithm every discrete point of the SDS is treated as a single resource, i.e. a spatial resource that can only be used by one aircraft at a given time. Thus, those spatial resources that are going to be used need to be reserved by aircrafts during a certain time window, the time window of utilization. This information is stored in the SDS, thus generating a kind of 4D snapshot that can be used for conflict detection (and resolution) purposes.

Aircraft safety envelopes can be modelled with 4D tubes, with an inner radius and a time duration defined according to the speed of the aircraft. A discretized version of these tubes is built and then stored in the SDS, where the conflict detection process is performed (see Fig. 4).



a) b)

c)

Figure 4. 4D tube construction (a), rotation (b) and location (c).

Fig. 5 shows an example of SDS content of two crossing trajectories as a 4D snapshot. Each of the discrete points of the safety envelopes is stored in the SDS. Fig. 2 is used to explain how this particular CD algorithm uses the stored reservations of resources (i.e. the spatial discrete cells) to perform the detection of conflicts among different aircraft.

To detect conflicts, at the moment of storing a tube-point the algorithm reads the first column. If its value is empty (i.e. equal to zero), as in the coordinate (0,0,0) it means that no other aircrafts intend to use such a coordinate, so this spatial resource can be booked without conflict. If the first column is not empty, then the algorithm compares the (explicit or implicit) time windows. If their time windows are overlapping, as it occurs between aircraft 3 and 4 in coord. (0,1,1), then a conflict is detected and the CR system is informed. If the time windows are not in conflict, it means that the coordinate might

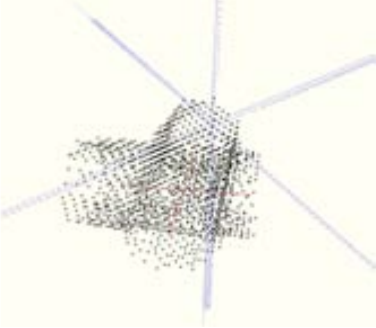


Figure 5. Two crossing trajectories

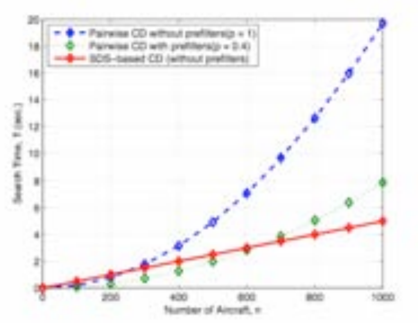


Figure 6. SDS-based performance (with 4D tubes) vs. pure pairwise CD

be booked in the following column; that is the case of aircraft 6 and 12 in coord. (0,2,0). In the following columns the same procedure is applied sequentially.

A spatial granularity of 100 meters between points of the discrete mesh has been considered, having taken into account the size of the aircraft and their safety envelopes, as well as the aircraft speeds (generally over 200 m/sec.) and the restrictions imposed by the quantity of RAM memory available. Tube convexity properties have been used to ensure that all the possible conflicts will be detected on the surface of the tubes (important computational time savings are possible by only processing the surface of the tubes).

Simulations of different TMA scenarios have provided excellent performance when processed with the SDS-based CD algorithm [13]. A formal demonstration of the linear temporal complexity O(n) of this algorithm, in contrast with the quadratic temporal complexity O(n^2) of the pairwise-based CD algorithms can be found in [14].

IV. USE OF THE STATE-SPACE STORED IN THE SDS

A. *Analysis of interactions among SBTs/RBTs and CR trials*

In STREAM, the CR module coordinates with the CD module to propose one or several manoeuvres to solve a conflict situation. These manoeuvres are based on *path shortening/path stretching* techniques and/or *speed regulations* that are applied to one or both trajectories in conflict [15].

With this kind of manoeuvres the CR algorithm generates one or more trial trajectories for each trajectory in conflict. These trial trajectories are then sent to the CD module to evaluate possible conflicts. Note that sometimes a manoeuvre that is intended to solve a conflict can generate other conflicts that previously did not exist in the ATM network. These network effects have been called *interactions* in this paper, and they can be classified as follows (see Fig. 7):

- *Primary conflict:* a conflict between 2 original SBTs/RBTs
- *Secondary conflict:* a conflict which emerges between a resolution manoeuvre proposed by CR to solve a primary conflict and a surrounding original SBT/RBT.
- *Tertiary conflict*: a conflict which emerges between 2 resolution manoeuvres belonging to any surrounding aircraft.

Original SBTs/RBTs may have more conflicts after their first conflict, which are referred as *downstream conflicts*. Resolution manoeuvres of the CR could also generate these, and in this case they would be referred to as *secondary downstream conflicts* (or *tertiary* if the conflict occurs between 2 trial trajectories proposed by the CR). Also note that resolution manoeuvres could also solve original downstream conflicts (see Fig. 8 and Fig. 9)

Recent research with a CR system based on Colored Petri Nets has validated the usability of the information on interactions stored in the SDS. Therefore, when a conflict is detected, and depending on the type of conflict, the CR algorithm chooses among a set of rules to propose a new trial solution, for example if a secondary conflict is detected, the algorithm keep trying manoeuvres till the conflict is solved (Fig. 8 and Fig. 9). More research is currently being performed to find better and more complex cooperative resolutions to highly congested scenarios.

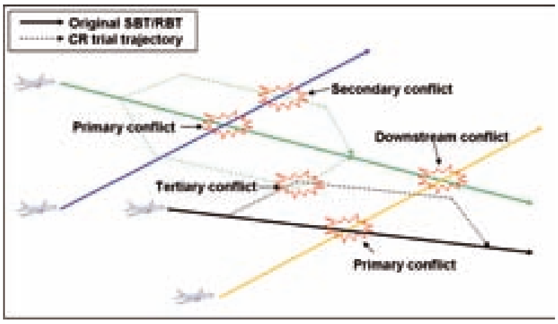


Figure 7. Interactions among SBTs/RBTs and CR trial trajectories

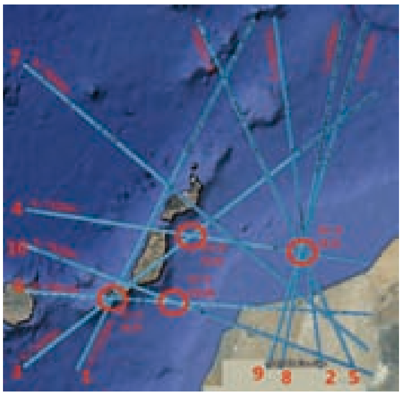


Figure 8. Scenario with 4 conflicts

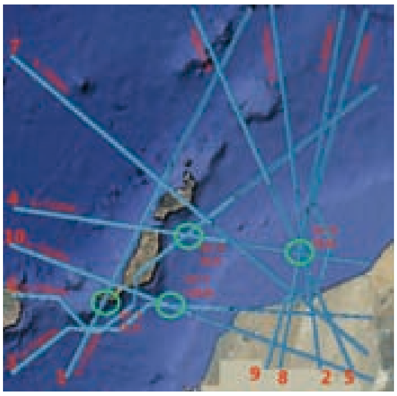


Figure 9. Scenario with 4 conflicts solved by CR

B. *Temporal/longitudinal looseness and sensitivity analysis:*

By analyzing the content of the SDS after processing the planned trajectories it is possible to quickly obtain the information about the *temporal/longitudinal looseness*, λ, for each trajectory, i.e. how much time a trajectory can be advanced or delayed without entering in conflict with another trajectory.

Formally, the temporal looseness λ can be defined as the time-window formed by the minimum and maximum *delays*, δ_{min} and δ_{max}, that a given trajectory can afford while still being conflict-free, having the rest of the trajectories static:

$$\lambda = [\ \delta_{min}\ ,\ \ \delta_{max}\ ] \qquad (2)$$

Note that δ_{min} could be negative, i.e. $\delta_{min} < 0$, if the trajectory can be advanced in time (see Fig. 10). In addition, both δ_{min} and δ_{max} are bounded by technical and service restrictions, such as the maximum increment of speed allowed for a given aircraft and the maximum deviation allowed from the user-defined Estimated Time of Departure (ETD) and Estimated Time of Arrival (ETA).

The calculation of λ can help the CR to provide resolutions based on speed regulations. Referring to Figure 2, the row of the SDS associated with the coordinate (0,1,1) shows aircraft 3 and 4 in conflict, since both aircraft want to use the same coordinate in incompatible time-windows (i.e., [34-154] for aircraft 3 and [32-152] for aircraft 4). Aircraft 7 also wants to use the same coordinate, but now the time window, [879-999], is not in conflict with any aircraft. The longitudinal looseness of aircraft 3 in this coordinate, (0,1,1), in which it can be delayed without entering in conflict with aircraft 7 is given by 789-154 = 725 time units. Assume there is no other coordinate for aircraft 3 with less looseness, so the total looseness of the trajectory for aircraft 3 is the same as calculated in point (0,1,1). It means that aircraft 3 can be delayed 725 seconds without entering in conflict with any other aircrafts. So, a possible way to solve the conflict between aircraft 3 and aircraft 4 is by delaying the ETD of aircraft 3 in 152-34 = 118 seconds. Since 118sec. is lower than 725sec., which is the total temporal looseness of aircraft 3, it is ensured that this delay will solve the conflict without creating a new one in the considered airspace.

On the other hand, a post-processing of the conflict-free trajectories stored in the SDS and their temporal looseness would also allow a sensitivity analysis regarding the influence of departure delays (i.e. on the ETD) of the RBT on the number of conflicts/interactions and on the complexity of their solution.

Thus, by analysing the different rows of the SDS it is possible to compute the following for each trajectory:

- The maximum departure delay δ_{max} (or advance δ_{min}) that could be accepted without generating a new conflict with other trajectories. This information is easily obtained by computing the minimum time distance between two adjacent columns. Information about the trajectories involved in each potential conflict is also provided.
- The number of conflicts given a certain delay out of the range of the trajectory longitudinal looseness, $\delta \notin \lambda$. This data should be provided together with some indicator describing the concentration or distribution in time of these potential conflicts. It is easy to see that knowing that an ETD delay could generate 25 potential conflicts is valuable information, however it lacks a complexity measure related to the resolution. The same information with a measure indicating that the 25 conflicts are concentrated in the same area, or are distributed

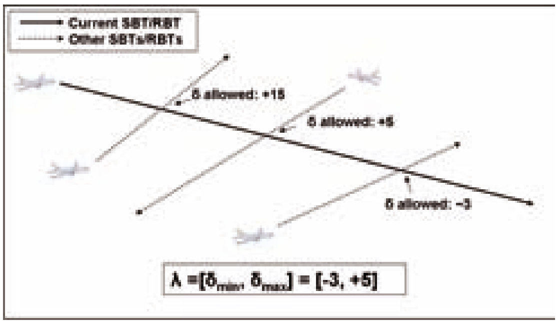


Figure 10. Scenario with 4 conflicts

along the trajectory, provides better knowledge about the impact of the delay on ATC workload.

The sensitivity analysis could provide highly valuable information on the airport departure schedule (DMAN), in trying to preserve the ETD of those flights that could generate extra-workload to controllers.

In addition, the constraints imposed on the strategically de-conflicted RBTs will allow the different actors involved to visualise the level of sensitivity of each trajectory to tactical modifications. This will help air traffic controllers in assigning priorities to different flights when it comes to tactically vectoring traffic (for whatever need) in order to minimize network impact by selecting the less constrained trajectories.

The concept of Target Window proposed by CATS project [11] is a good choice to easily represent the resulting constraints and their degree of looseness: these are 4D windows located at sensitive points along the trajectory, depending on airspace configuration and ATM needs.

A set of metrics and methods to obtain and synthesize the information stored in the SDS which is of interest for the sensitivity analysis, also taking into account uncertainties and the probability of conflicts, is currently under development within STREAM.

C. *Network analysis:*

The content of the SDS can be also studied from a network perspective, by aggregating the information about the interactions, looseness and sensitivity for a selected set of trajectories (e.g. a specific conflict-free scenario) in order to generate new aggregated metrics and ratios able to explain the behaviour of the ATM as traffic flows rather than as single trajectories.

For example, it could be useful to take into account the aggregated flows and the different probabilities of conflicts and interactions, with their inner uncertainties in space and time, in order to analyse and generate a complexity map of the network.

Once a conflict-free scenario is selected, the traffic stored in the SDS on this scenario will represent a reliable picture of the traffic for a time horizon of 2-3 hours, thus allowing the NM to identify congested areas and hot spots and to plan necessary actions, such as sizing the ATM with the appropriate resources or creating alternative plans to deal with contingencies.

The analysis of the rows of the SDS can also provide useful information about the demand that airspace users produce over a specific spatial resource, i.e. a discrete coordinate. A sector demand analysis is also possible by aggregating the information of the rows according to the coordinates that belong to a specific sector, which could be of interest in the process of demand/capacity balancing.

A set of metrics and methods to generate network knowledge from the information stored in the SDS is currently under development within STREAM project.

V. CONCLUSIONS AND FUTURE WORK

A CD based on SDS has been presented as a fundamental part of the STREAM project, investigating the feasibility of strategic conflict detection & resolution on the Shared Business Trajectory.

The CD algorithm based on SDS presents 2 advantages with respect to classical CD algorithms (i.e. pairwise algorithms):

- Its temporal complexity is linear (i.e., it process trajectories in linear time).
- It is able to store the state-space of the ATM.

A linear temporal complexity allows the processing of large numbers of trajectories (i.e. tens of thousands) in a very efficient time window (i.e., seconds, with a medium power computer). This ability is a key factor to complement those CR algorithms that work by proposing different trajectory trials to solve the detected conflicts, since they can considerably increase the total quantity of trajectories to be processed.

The ability to store the state-space means that once all the trajectories have been processed (both the original SBTs/RBTs and the CR trials), all of the information remains in the SDS, with all the found resolutions and also with non-acceptable trajectories. This ability is useful to complement those CRs that want to explore the interactions between their proposed trial trajectories and the rest of trajectories in the network. Since all the trajectories remain stored in the SDS, even the trials proposed by CRs, it is possible to detect conflicts among these trials and the original SBTs/RBTs (i.e. secondary conflicts) or even among other trial trajectories (tertiary conflicts) and then to take advantage of this qualitative information to improve the conflict resolution process.

In addition, having the state space stored in the SDS allows different kinds of post-processing to be performed in order to obtain useful information about the ATM. For example it is possible to obtain the temporal looseness for each trajectory of interest, since it is quite straightforward to calculate how many minutes or seconds a given trajectory can be advanced or delayed without creating interactions (i.e. conflicts) with other accepted trajectories.

Another example of post-processing analysis over the SDS content could be a sensitivity analysis for a set of trajectories of interest. This would allow the generation of information on how many interactions a trajectory could generate in the network if the final RBT were changed by tactical requirements. This information would be useful for tactical controllers in order to apply tactical/operational changes over those trajectories with less impact on the rest of the network.

In the same way, an aggregated sensitivity analysis could generate useful information about the network, such as the identification of hot zones in the ATM system, which would allow the dimensioning of the requirements for each zone (i.e. the number of controllers) and the calculation of the capacity of the air sectors.

Simulation experiments have validated the ability to explore some of the interactions among trial trajectories proposed by a CR specified in Coloured Petri Nets formalism (used in STREAM project). However, more research should be done to explore the information stored in the SDS on the secondary and tertiary conflicts in order to obtain more efficient resolutions (i.e. global cooperative resolutions).

A set of ratios and metrics are currently under development with the intention of illustrating and synthesizing the information obtained in the state-space post-process experiments. This information should be useful in order to have a better understanding of the ATM and make better decisions at strategic and tactical/operational levels, and also to perform efficiency/efficacy analysis of the CR proposals and make comparisons among different CR algorithms.

A series of simulations will be run to validate the concept, based on current and forecast traffic scenarios. For each one, an ideal baseline will be defined by running the simulation without any ATM intervention, assuming all flights are hypothetically conducted as user-preferred Business Trajectories subject only to the applicable static airspace constraints. This will establish the maximum level of efficiency achievable from the users' perspective. Then, each of the scenarios will be run on the trajectories already de-conflicted by the STREAM solution, i.e. on the amended ones. Several disturbances (wind, delays, etc.) will be introduced in the simulation to test the robustness of the amended trajectories under conditions of uncertainty. This will make possible to establish requirements on the accepted tolerances in the trajectory information at the pre-departure stage. A stochastic analysis will be conducted to estimate the probability of tactical interventions due to resolution of conflicts which were assumed to be solved by the STREAM solution already at the planning level.

ACKNOWLEDGMENT

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7.4 *"Causal Decision Support Tools for Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management (STREAM)"*

Article 4, "*Causal Decision Support Tools for Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management (STREAM)*", has been published in the SESAR Innovation Days (SID) conferences. It presents the advances achieved in the use of the ATM 4D information available through the SDS by integrating an improved version of the conflict resolution module based on causal modelling to deal with the emergent dynamics of the air traffic system. This paper gives details of the conflict resolution algorithm specified in Coloured Petri Nets and presents some of the preliminary results found at that moment during STREAM project execution. In addition, an important strategy to deal with the highly interactive European network with more than 4000 trajectories crossing European airspace at certain peak hours of traffic is also presented, the Clustering causal model, which allows reducing the global problem to a set of unconnected sub-problems, thus considerably reducing the combinatorial state-space search of the problem and the time required to solve it.

Causal Decision Support Tools for Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management (STREAM)

Clustering and Interaction Causal Solver Models

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Foreword - This paper describes a project that is part of SESAR Work Package E, which is addressing long-term and innovative research.

Abstract— SESAR WP-E STREAM project seeks to fill a currently existing gap between the strategic and the tactical planning in ATM, by designing innovative tools capable of detecting and solving conflicts among aircraft in a time-efficient manner, in order to deliver traffic to ATCOs with a diminished number of conflicts. In this paper, Clustering and Interaction Causal Solver (ICS) models are presented, being developed under the formalism of Colored Petri Nets for the generation of several feasible conflict free solutions. By clustering, the computational complexity is significantly reduced. The separation of trajectories according to their interactions is the key idea in high-density traffic scenarios, bringing several benefits such as a direct increase of processing capacity and troubleshooting. In the same direction, the ICS model makes an intelligent construction through the use of causal interactions, thus limiting the search exploration process only to those combinations supported within each cluster. Therefore, both tools offer significant advantages over the efficiency and effectiveness for the construction and evaluation of Air Traffic Management conflict-free scenarios. According to the STREAM concept, these models produce multiple combinations of feasible conflict free solutions, to be later weighted according to different metrics (for efficiency, safety, robustness, equity and fairness among others) and selected **based on stakeholders' priorities.**

Considered as a whole, the decision support tool , once implemented, provides a new and efficient network-oriented conflict detection and resolution process, fitting into the overall performance framework currently implemented at European level.

Keywords-Strategic ATM; Causal Modeling; Decision Support Tools; Colored Petri Nets.

I. INTRODUCTION

SESAR WP-E project STREAM (Strategic Trajectory de-confliction to Enable seamless Aircraft conflict Management) [http://www.hala-sesar.net/stream] is currently being undertaken by a consortium composed of Advanced Logistics Group (ALG-Indra), Boeing Research & Technology Europe (BR&TE) and Universitat Autònoma de Barcelona (UAB). The project aims to fill the current existing gap between the strategic and the tactical planning in ATM, by designing Conflict Detection & Resolution (CD&R) tools that re-organize air traffic at strategic level (thus, diminishing the amount of conflicts to be solved at a tactical level), while generating useful network information in order to improve the decision making process [1].

For a thorough description of the concept and of the high level architecture of the STREAM solution, the reader is referred to [3]. Several results have been obtained under project activities during the course of 2012, within the different technical Work Packages: WP2 Strategic trajectory de-confliction tool development, WP3 Metrics & methodology development and WP4 Analysis & evaluation. This paper however focuses only on the algorithmic innovations related with the conflict resolution thread of the research. These innovations were achieved under WP2 and have been selected for publication due to their interest for scientific community and maturity for presentation. The work in WP3 and WP4 is underway and results should be available for presentation within the next few months.

The approach proposed by WP2 for conflict resolution is based on the generation of several resolution trajectories per conflict and on a post-processing activity based on the causal network interactions. This determines several conflict-free network solutions or network solutions with a diminished number of conflicts (*i.e.* several final states).

This paper presents the details of the Clustering and Interaction Causal Solver sub-models within the CD&R architectural framework, which are functional to the generation of several feasible conflict-free solutions.

II. PROBLEM DESCRIPTION

The architectural framework for CD&R developed under the STREAM project, is summarized in figure 1 and basically consists of:

- A Conflict Detection (CD) module which analyzes the different trajectories under study by means of a Spatial Data Structure.
- Resolution Trajectory Generator (RTG) module to solve the conflicts at trajectory level by implementing Heading Angle Change (HAC) procedures.
- Clustering (C) and Interaction Causal Solver (ICS) to detect network interactions between trial trajectories and propose conflict-free scenarios at network level.
- A communication interface to coordinate the CD, RTG and C/ICS modules.

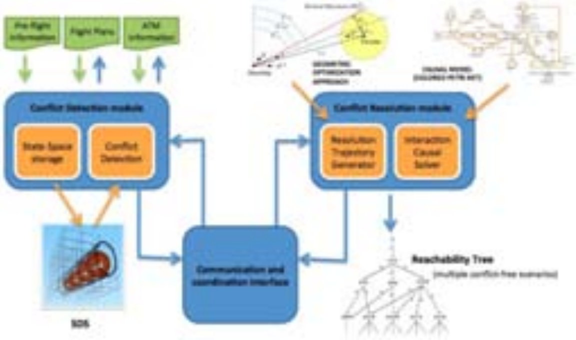

Figure 1. STREAM solution architecture.

Spatial Data Structures (SDS) permit the conflict detection problem to be reduced to a linear complexity O(n) and at the same time they provide a very natural representation of the status of the Air Traffic Management (ATM) system and of its evolution over time. The state-space information stored in the SDS by the conflict detection module can be used by the conflict resolution algorithm to calculate the trajectory amendments; a detailed explanation of SDS is presented in [1] and details of the conceptual and technological framework in [2].

To provide air traffic controllers with conflict free traffic scenarios, several trajectories must be generated in the resolution of each conflict detected at local level, but a global analysis considering the interactions of the proposed amendments at network level is required to determine the feasible solutions. This conclusion is one of the preliminary results obtained in the STREAM project [3]. Figure 2 illustrates a couple of scenarios with different conflicts between 4-Dimensional Trajectories (4DT's) and two alternative new trajectories to solve the conflicts at local level.

At the left hand side of the figure, a conflict (nc1) between two trajectories (Tr1 and Tr2) together with alternative HAC trajectory resolution (Tr11 and Tr12) is represented. Thus, considering at local level conflict nc1, the Conflict Resolution (CR) would provide as feasible solutions the combinations Tr1 and Tr21 or Tr11 and Tr2. By considering also the conflict nc2 between trajectories Tr3 and Tr4 together with their local resolution trajectories (ie. Tr31 and Tr41) the new set of feasible solutions is extended to:

Tr1,Tr21,Tr3,Tr41

Tr1,Tr21,Tr31,Tr4

Tr11,Tr2,Tr3,Tr41

Tr11,Tr2,Tr31,Tr4.

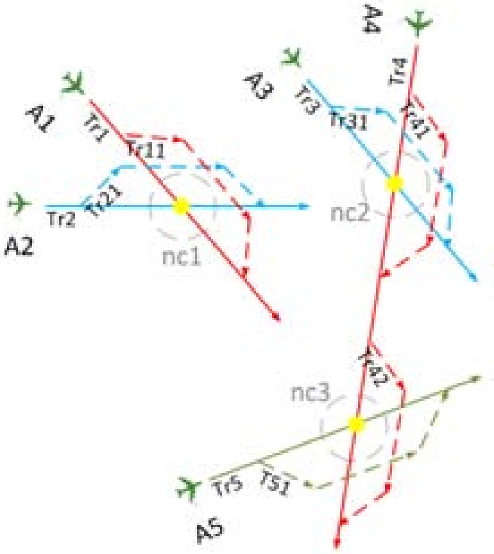

Figure 2. Example of an air traffic scenario

However, by considering the existence of two conflicts (nc2 and nc3) between aircraft A4 with A3 and A5, a new dynamic behavior must be considered in the computation of feasible solutions since conflict nc3 appears only if conflict nc2 is solved by implementing trajectory Tr31 without requiring the computation of resolution trajectories Tr42 and Tr51. It should be noted that the existence of conflict nc3 depends on upstream decisions (i.e. earlier events within the system) since the implementation of trajectory Tr41 introduces a downstream time modification that can incur new conflicts or remove original ones. At a network level, conflict nc3 can be resolved without the need to implement Tr42 or Tr51, just by implementing a combination considered in trajectory Tr41.

The above network logics can and should be exploited in the analysis and resolution of traffic scenarios to generate conflict-free feasible solutions, by exploring the interactions between possible local conflict free solutions: The implementation of an alternative trajectory can avoid a local conflict and also inhibit a downstream conflict.

Other examples of emergent dynamics (cascade effects) [4] for such systems are the secondary conflicts between planned trajectories and resolution paths as illustrated in Figure 3, or even tertiary conflicts, that are artificially incurred by the local resolution trajectories between different conflicts [5]. From this point of view it is important to analyze and process resolution scenarios at network level, considering the interactions between the original and the generated resolution trajectories.

Cascade effects are not a minor issue, considering the volume of traffic and possible conflicts between planned trajectories. For simplicity, in this paper only one alternative resolution trajectory is considered for each aircraft involved in a conflict, however, for practical purposes usually more than one alternative trajectory is generated, which increases the complexity of the resolution trajectory interaction effect analysis.

Under a causal approach, considering the interactions (conflicts and emergent dynamics) between aircraft and their trajectories, it is possible to analyze the resolution trajectory interaction effects at network level and generate a set of efficient feasible conflict free solutions.

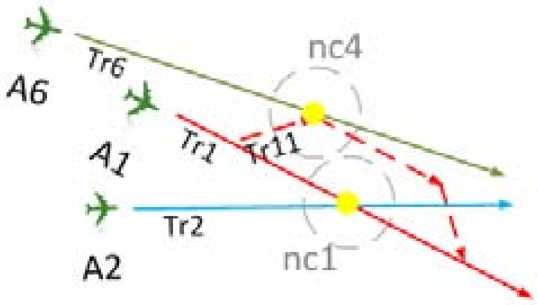

Figure 3. Examples of a cascade effect.

III. CAUSAL MODELING FRAMEWORK

Colored Petri Net (CPN) approach is a high level modeling formalism for complex systems that has been widely used to model and verify systems, allowing representation of not only the system dynamics and static behavior but also the information flow.

The main CPN components that fulfill the modeling requirements are:

- Places: These are very useful to specify both queues and logical conditions, represented by circles.
- Transitions: These represent the events of the system, depicted by rectangles.
- Input arc expressions and guards: These are used to indicate which type of tokens can be used to fire a transition.
- Output arc expressions: These are used to indicate the system state change that appears as a result of firing a transition.
- Color sets: Determine the types, operations and functions that can be used by the elements of the CPN model. Token colors can be seen as entity attributes of commercial simulation software packages.
- State vector: The smallest piece of information needed to predict the events that can appear. The state vector represents the number of tokens in each place, and the colors of each token.

The color sets will allow the modeler to specify the entity attributes. The output arc expressions make it possible to define which actions should be coded in the event routines associated with each event (transition). The input arc expressions, in turn, make it possible to see when and why an event can appear, and consequently introduce new pre-conditions (or removing them) in the model, or alternatively change some variable or attribute values in the event routines to disable active events.

From the Operational Research (OR) point of view, the CPN model provides the following mathematical structures:

- Variables: A variable can be identified for each color specified in every place node.
- Domains: The domains of the variables can be easily determined by enumerating all the tokens specified in the initial state.
- Constraints: Can be obtained straightforwardly from the arc and guard expressions. Arc expressions can contain constant values, color variables or mathematical expressions.

From the Artificial Intelligence (AI) point of view, the coverability tree of a CPN model makes it possible to determine:

- All the events that could appear according to a particular system state.
- All the events that can set off the firing of a particular event.
- All the system states (markings) that can be reached starting from a certain set of initial system operating conditions M0.
- The transition sequence to be fired to drive the system from a certain initial state to a desired end-state.

Different approaches have been developed to combine the high description capabilities of simulation models with the benefits of analytical techniques of optimization models that have been proposed in several simulation–optimization approaches. One of the most classical and widely accepted has been the parameterization of the decision variables of the simulation model in such a way that an optimization algorithm can efficiently check the results of the most promising decision variable values. At the end of the procedure it compares the different system outputs and keeps the best of the solutions obtained [6].

IV. CLUSTERING (C) AND INTERACTION CAUSAL SOLVER (ICS) MODELS

The complexity (*i.e.* state space size) of the interaction causal analysis between original and resolution trajectories increases considerably with the amount of trajectories to be analyzed. Thus, it is proposed to identify a set of independent groups of trajectories which do not share any conflict and analyze each subset from the causal point of view by avoiding the combinatorial explosion problem. It is easy to realize that a set of trajectories distributed physically in 2 non coupled areas would lead to 2 different clusters. However, it should be noted that the fact that trajectories share a physical area does not imply that they all belong to the same subset. An efficient clustering causal model has been developed under the formalism of Colored Petri Nets and it is represented in figures 4 and 5a and 5b. Tables I to VI describe the place nodes, transitions and color of each token.

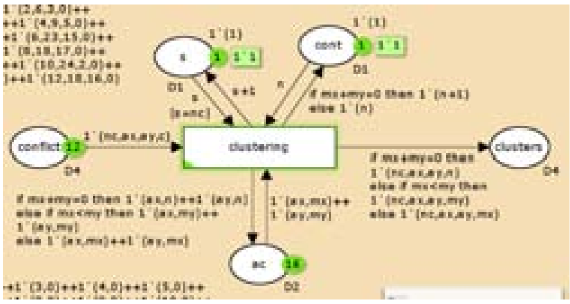

Figure 4. Clustering model in CPN formalism.

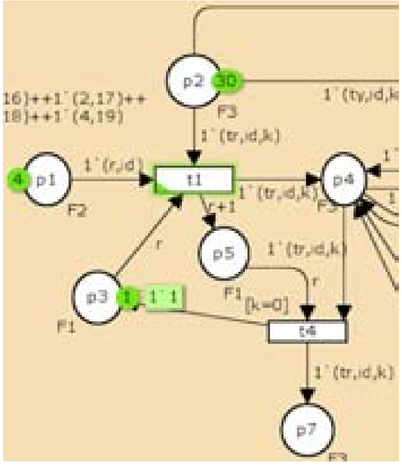

Figure 5a. Interaction Causal Solver (ICS) in CPN formalism (Trajectory picking section).

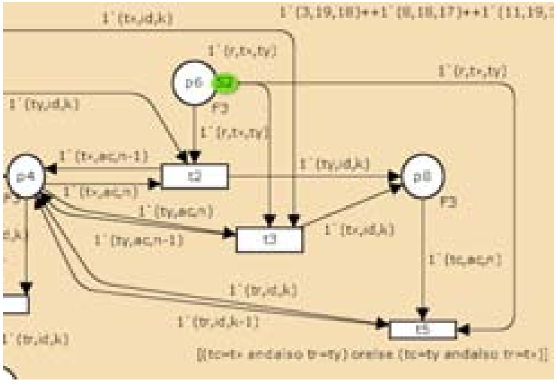

Figure 5b. Interaction Causal Solver (ICS) in CPN formalism (Trajectory interaction analysis section).

A. Clustering model

List of place nodes in the model:

- Conflict: set of conflicts (nc) between two aircraft (ax and ay).
- Ac: set of aircraft (ax and ay) with original conflicts (nc).
- S: switch for the sequence of analysis (starts in 1).
- Cont: cluster (n) to be assigned to each conflict (c) together with the aircraft (mx and my) involved.
- Clusters: conflicts processed with a cluster number.

The *clustering* transition evaluates for each conflict and the related aircraft the cluster where trajectories should be assigned.

To form clusters, the model uses the interactions between aircraft and conflicts, and theses clusters can be analyzed separately more efficiently as subsystems in the ICS (Interaction Causal Solver) model.

TABLE I. COLOR DEFINITION IN CLUSTERING MODEL

Colors	Description	
	Definition	*Explanation*
S	Int 1…N	Sequence number
nc	Int 1…N	Conflict number
ax,ay	Int 1…N	Aircraft id
N	Int 1…N	Cluster counter
C	Int 1…N	Cluster number on conflicts
mx,my	Int 1…N	Cluster number on aircraft

TABLE II. PLACES IN CLUSTERING MODEL

Places	Description	
	Colors	*Explanation*
conflict	nc,ax,ay, c	The tokens placed here correspond to all the conflicts (interactions between pairs of aircraft) of the global scenario or system.
ac	ax,mx ay,my	The tokens placed here correspond to all the aircraft in the global scenario or system.
s	s	This token is the sequence number for processing the conflicts.
cont	n	This token is the sequence number to assign conflicts.
clusters	nc,ax,ay, c	In this place, the tokens are removed from the set of conflicts once a cluster has been assigned.

TABLE III. TRANSITIONS IN CLUSTERING MODEL

Transitions	*Explanation*
clustering	Picking of conflicts and aircraft to assign the corresponding cluster number based on the preprocessed conflicts.

B. *Interaction Causal Solver (ICS) model*

List of place nodes in the model:

- P1: set of aircraft (id) with a sequence number for being processed (r).
- P2: set of trajectories to avoid original conflicts (tr), for each aircraft (id) and with the number of interactions in the system (k).
- P3: switch for the sequence of analysis (starts in 1).
- P4: trajectory to be analyzed once it has been picked.
- P5: the next aircraft to be processed.
- P6: set of interactions between the set of trajectories.
- P7: set of selected trajectories for the conflict free solution
- p8: set of non-compatible trajectories, after the analysis of interactions against a picked trajectory.

TABLE IV. COLOR DEFINITION IN INTERACTION CASUAL SOLVER (ICS) MODEL

Colors	Description	
	Definition	*Explanation*
r	Int 1…N	Sequence number
id	Int 1…N	Aircraft id
tr	Int 1…N	Trajectory id
k	Int 1…N	Total interactions for a trajectory
tx, ty	Int 1…N	Trajectory id
ac	Int 1…N	Aircraft id
n	Int 1…N	Total interactions for a trajectory
tc	Int 1…N	Trajectory id

TABLE V. PLACES IN INTERACTION CAUSAL SOLVER (ICS) MODEL

Places	Description	
	Colors	*Explanation*
p1	r, id	Tokens stored here represent the aircraft involved in the scenario for which a path should be assigned and in this case are processed according to the value of r from lowest to highest.
p2	tr, id, k	The tokens stored here correspond to the feasible paths, defined for each plane and which have the number of interactions.
p3	r	This token is a sequence number
p4	tr, id, k tx, ac, n ty,ac, n	When depositing a token in this place it is because you chose a path for an aircraft, for further analysis of the trajectory's compatibility with the rest of the aircraft.
p5	r	This place is assigned the following sequence and functions as a switch.
p6	r, tx, ty	In this place you have stored conflicts which identify interactions between pairs of trajectories.
p7	tr, id, k	Here the trajectories analyzed and processed (feasible scenarios and unconflicted) are stored.
p8	tr, id, k tx, ac, n ty, ac, n	In this place, the trajectories discarded based on interactions with the selected paths are stored.

TABLE VI. TRANSITIONS IN INTERACTION CAUSAL SOLVER (ICS) MODEL

Transitions	*Explanation*
T1	Choice of a trajectory for an aircraft
T2	Analyzes the interactions of the trajectory with respect to the trajectories of other aircraft, eliminating those with any conflict. (tx case)
T3	Analyzes the interactions of the trajectory with respect to the trajectories of other aircraft, eliminating those with any conflict.
T4	Once all interactions of a trajectory have been processed the next aircraft is choosen.
T5	Analyzes if previous steps have eliminated the interactions, which no longer exist in the set of trajectories.

The core idea of the ICS model developed is to assign one conflict-free trajectory per aircraft in each feasible solution.

Since there will be different alternative trajectories for each aircraft in conflict there will also be many combinations among them that lead to several feasible conflict free solutions. To find these feasible solutions, the algorithm uses the information on the interactions and the information on the alternative and original generated trajectories.

At the end of the process, several combinations of feasible conflict-free solutions are delivered. By applying different metrics to measure efficiency, safety, robustness, equity and fairness, among other criteria, it would be possible to determine which of the feasible conflict-free solutions is the most preferred, for both the airlines and the Network Manager [4].

V. CASE STUDY, SIMULATION AND RESULTS

In order to show the performance of Clustering and ICS models, a synthetic scenario is presented, featuring 16 aircraft with 12 primary conflicts, and 91 secondary and tertiary conflicts.

Table VII presents the data and figure 6 shows the results for the clustering analysis, and the resultant clusters are listed in table VIII.

TABLE VII. SYNTHETIC SCENARIO

Aircraft	*Trajectories* ***Tr1, Tr2, Tr3…TrN***	*Primary Conflicts (nc, tx, ty)*
2	2	(1,9,8)
3	3,289,315,1589,1615,1641,1667	(2,6,3)
4	4,1590,1616	(3,19,18)
5	5,811,837	(4,9,15)
6	6,292,318,1072,1098	(5,10,6)
8	8,34,60	(6,23,15)
9	9,35,61,815,841,867,893	(7,4,3)
10	10,1076,1102	(8,18,17)
15	15,1341,1367,2121,2147,2173,2199	(9,20,15)
16	16,2902,2928	(10,24,2)
17	17,1863,1889,2643,2669,2695,2721	(11,19,17)
18	18,564,590,1864,1890,1916,1942,2904,2930,2956,2982,3008,3034	(12,18,16)
19	19,565,591,2645,2671,2697,2723	
20	20,2126,2152	
23	23,1349,1375,1401,1427	
24	24,2390,2416	

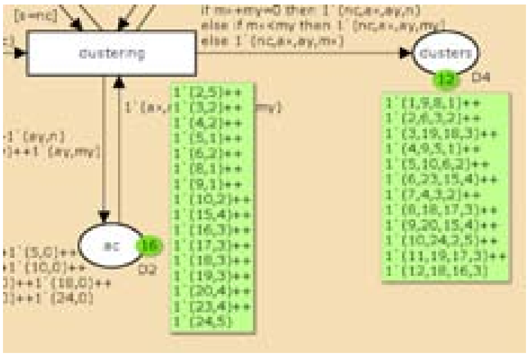

Figure 6. Clustering results in the Colored Petri Net.

TABLE VIII. LIST OF CLUSTERED CONFLICTS

Cluster	*Conflicts*
1	1,4
2	2,5,7
3	3,8,11,12
4	6,9
5	10

With the complete information (aircraft, trajectories and interactions), each cluster is introduced in the ICS to generate feasible conflict free solutions. Figure 7 presents the initial state for cluster number 3, including: 4 aircraft 16, 17, 18 y 19, and 30 trajectories and 52 interactions (primary, secondary and tertiary conflicts).

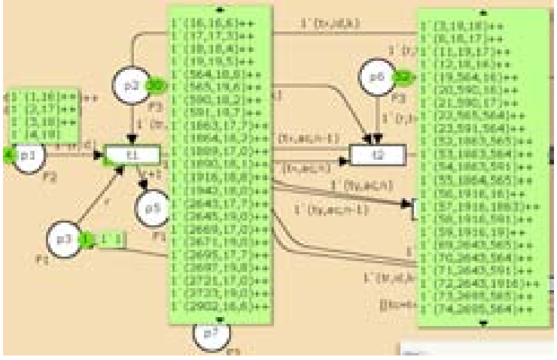

Figure 7. Initial conditions for the ICS Colored Petri Net

Figures 8 and 9 show the two conflict-free solutions (final states) which have been obtained through the state space analysis tool. Place 7 holds the final repository of conflict-free trajectories obtained, wherein the first color is the trajectory id, the second is the aircraft id, and the third is the number of interactions after the process. A feasible solution is obtained when the amount of tokens in place 7 is equal to the amount of aircraft.

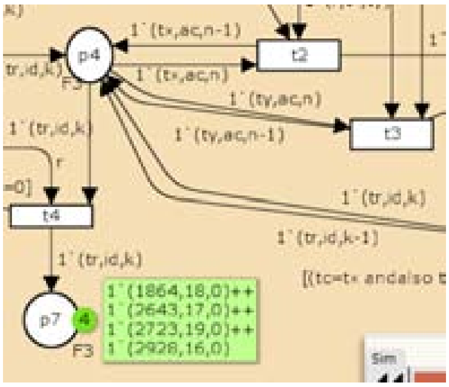

Figure 8. One Feasible conflict free solution for cluster 3.

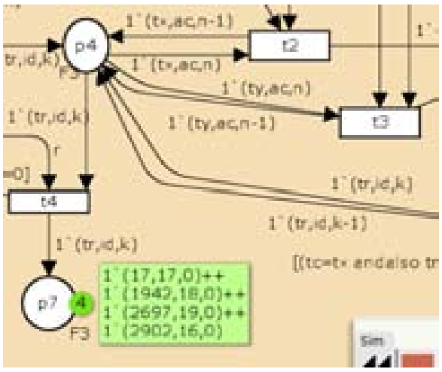

Figure 9. Another Feasible conflict free solution for cluster 3.

Despite the fact that the entire set of feasible solutions (final states) can be explored in the coverability tree, not all the feasible solutions may be of ATM interest, meaning that an efficient and effective search is necessary.

The causal framework and the formalism explained is capable of including some individual metrics (as an additional color) that provide intelligence for the process.

For example, it is possible, by ranking each alternative trajectory (under considerations of fuel consumption, or additional time, etc.) to reflect the preference for certain solutions. Figure 10 presents transition T4 l, with three additional places (*kpi, kpi value per trajectory, acum kpi*), connected to the transition, which are used to perform a metric assessment.

According to the value of the KPI, the models keep or discard the scenarios that do not match the expected performance.

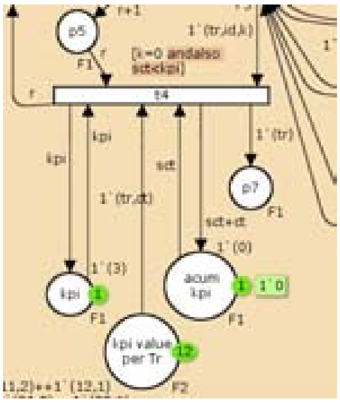

Figure 10. Metric assessment addition.

This structure can be replicated to other metrics and the assessment can be performed by the model simultaneously during the construction of the state space.

The construction of supported combinations of paths is a problem that grows in an expansive way (quadratic and sometimes exponential). To mitigate this problem, the clustered approach, prior to the construction of conflict free scenarios and as described above, allows a significant minimization of the State space size, by grouping the trajectories which have some kind of conflict relationship. As a first step, it is proposed to determine the number of possible trajectory combinations and, in a second step, to assess the compatibility of each local conflict-free trajectory.

By considering an equal amount of alternative trajectories per aircraft for all cases, the number of combinations to render, without clustering, would be K^N, where N corresponds to the number of aircraft and K the number of trajectories of each aircraft. In the proposed example, K is different for various aircraft. Therefore, the number of combinations would be: $(K_{Ac1})(K_{Ac2})(K_{Ac3})...(K_{Ac16})$.

Taking the values in Table VII, the amount of possible combinations is:

$$(1)(7)(3)(3)(5)(3)(7)(3)(7)(3)(7)(13)(7)(3)(5)(3) = 1.19 \cdot 10^{10}$$

On the other hand, considering each cluster separately, the number of total combinations is reduced considerably as a combination of the solutions provided in each cluster:

$$(1)(3)+(3)(7)(13)(7)+(7)(3)(5)(3)+(3)(3)(7)+(7)(5)(3)$$

$= 3+1911+315+63+105 = 2.397 \cdot 10^3$ possible combinations.

It is important to mention that not all possible combinations represent compatible conflict-free solutions.

The computational complexity is significantly reduced by clustering. The separation of trajectories according to their interactions is a key idea in high-density traffic scenarios and it deals with several benefits such as a direct increase of processing capacity and troubleshooting.

In the same direction, the ICS model, through the use of causal interactions, makes an intelligent construction by limiting the search exploration process only to those combinations supported within each cluster. Therefore, both tools offer significant advantages in terms of efficiency and effectiveness for the construction and evaluation of conflict-free scenarios in Air Traffic Management problems.

The discrete event-modeling approach—which reflects the dynamic and adaptive behavior of the system and, in turn, provides intelligence on the exploration of their evolution (this capacity is intrinsic in Colored Petri Net models)—plays an important role and draws significant advantages with respect to other tools and analytical techniques such as PL or MIP, methods that have traditionally been used to develop models for decision making in ATM.

For the synthetic example in general, as well as for each cluster separately, the ICS is able to obtain feasible solutions. Additionally, it ensures the existence of feasible combinations by generating as many alternative paths as there are conflicts detected and builds a path to avoid the conflict. In the event that such a trajectory is involved in a new conflict, another path is generated.

The two models presented have the capacity to generate feasible solutions in a reduced computational time either via simulation or by exploring the space of states. STREAM considers further evaluation of the complete platform with scenarios related to the full extent of pan European air traffic during a time window of 3 hours, with the aim to assess the performance and validation of different models (efficiency and effectiveness), including the calculation of KPIs for each scenario in such a way that it can find optimal or near-optimal values for a better strategic decision.

The primal application of the resulting tool is the strategic or pre-tactical de-confliction of trajectories, which could be triggered either by the Network Manager, due to the centrality of its role or directly by the ANSP in close coordination with the NM. The Airspace Users could be involved either directly into the process to ensure maximum visibility of its evolution or off-line through the initial definition of priorities. The use of a dedicated SWIM-based application constitutes the best candidate technology for implementation, since this is going to be established as a standard in ATM and some preliminary tests for flight data retrieving have shown excellent performances in terms of response times and stability. The Human actor, being the traffic manager or the ATCO, will be supported by the tool in identifying the best solutions in terms of conflict-free trajectories but will remain the ultimate responsible for selecting and activating the ones retained as valid. The agreement process should occur exactly as the one engineered by SESAR for the transition from SBT to RBT.

VI. CONCLUSIONS

Some of the emergent dynamics of an air traffic scenario have been shown through the presentation of causal modeling approach, clustering and Interaction Causal Solver (ICS) models. The construction of conflict free scenarios, as described above allows a significant minimization of the State space size, by grouping those trajectories which have some kind of conflict relationship.

This framework appears to be an effective approach for dealing with the emergent dynamics of an air traffic management scenario.

Not only has it been shown that a feasible conflict-free solution can be obtained for a particular synthetic European scenario, but it has been implicitly shown how this approach is extensible to the search of local or global, optimal and feasible conflict-free solutions.

In a scenario over the European ATM, with more than 4500 real trajectories of 1 hour average-length (sampled every 1 second), approximately 400 conflicts were detected in less than 10 seconds, and ICS responded by porposing conflict-free scenarios in less than 30 seconds. The hardware used in the simulations was a medium-range computer (10,000 MIPS) with 64GB RAM (around 40GB were used during the simulation).

The next steps to be undertaken are the development and implementation of metrics calculation; generation of criteria for selection of optimal solutions; development of performance analyses with more complex and denser scenarios; and, finally, the assessment of the advanced STREAM solution integrating latest innovations implemented.

STREAM outcomes fit into a V0 validation level within E-OCVM, extracting the specific needs for a trajectory de-confliction tool at strategic level. However, it also has traces of V1 validation step since it integrates assessments and tests of specific modules that solve some specific needs.

Stemming from this initial validation provided by STREAM (between V0 and V1), further steps towards the generation of a real decision support tool might be taken in more than one direction. The future developments can be derived in two main threads that can be combined. On one hand, it can focus on the specific development and refinement of the conflict detection and resolution with the aim of validating and producing an actual specific tool or application. Alternatively, on the other hand, the future developments can capitalize STREAM valuable outcomes and extrapolate their benefits to be used as a base for decision support tools addressing problems other than only de-confliction, such as demand/capacity balancing and complexity management.

The concepts used in STREAM algorithms can, therefore, be the input to generate new algorithms that focus on the optimization of trajectory design accounting for multiple KPAs and factors affecting the network. This approach would lead to a more thorough integration within a real and more ATM-extended decision support tool that could be used by different stakeholders (e.g. traffic manager, ANSPs, Airspace Users…).

ACKNOWLEDGMENT

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7.5 "*Strategic de-confliction in the presence of a large number of 4D trajectories using a causal modeling approach*

Article 5, "*Strategic de-confliction in the presence of a large number of 4D trajectories using a causal modeling approach*", is at the moment of writting these lines in a "conditionally accepted" state in the journal of Elsevier Transportation Research part C. It gives detailed information about the final architecture and logical functioning of the CD&R used in STREAM. It also describes in detail the causal model applied in the conflict resolution module, which works in a and cyclical way with the SDS. Final results of the STREAM project (complementary to the results presented in Chapter 5) after the strategic de-confliction of a nominal scenario with more than 4000 trajectories flying within the European airspace can be also found.

Strategic de-confliction in the presence of a large number of 4D trajectories using a causal modeling approach

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This paper presents a strategic de-confliction algorithm based on causal modeling developed under the STREAM project and launched under the umbrella of the Single European Sky ATM Research (SESAR) Program. The basic underlying concept makes use of the enriched information included in the Shared Business Trajectories (SBTs) of the flights prior to takeoff (or in the Reference Business Trajectories (RBTs) if the flight is airborne) to allocate conflict-free trajectories in a traffic planning phase that should lead to an actual conflict-free scenario in the flight execution phase in the absence of flight and/or network uncertainties. The proposed approach could decrease the workload of the air traffic controllers, thus improving the Air Traffic Management (ATM) capacity while meeting the maximum possible expectations of the Airspace Users' requirements in terms of horizontal flight efficiency. The main modules of the implemented system are also presented in this paper; these modules are designed to enable the processing of thousands of trajectories within a few seconds or minutes and encompass a global network scope with a planning horizon of approximately 2 to 3 hours. The causal model applied for network conflict resolution and flight routing allocation is analyzed to demonstrate how the emergent dynamics (i.e., domino effects) of local trajectory amendments can be efficiently explored to identify conflict-free Pareto-efficient network scenarios. Various performance indicators can be taken into account in the multi-criteria optimization process, thus offering to the network manager a flexible tool for fostering a collaborative planning process.

Keywords: 4D trajectories, causal analysis, strategic conflict detection and resolution, strategic de-confliction, dynamic route allocation, SESAR programme

1. INTRODUCTION

The 4D Business Trajectory constitutes a fundamental element of the SESAR Target Concept for 2020, which is aimed at evolving from the current airspace-based ATM system to a trajectory-based system designed to accommodate Airspace Users' (AUs) requests to the maximum extent possible (SESAR Consortium, 2007). The Business Trajectory is expressed for each flight in space and time and evolves out of a collaborative layered planning process, from the form of the Shared Business Trajectory (SBT), which is shared with all the involved stakeholders for planning and negotiation purposes, to the Reference Business Trajectory (RBT), which is implemented a few minutes before flight execution and represents the trajectory through which the Airspace User agrees to fly and that the Air Navigation Service Providers (ANSPs) and airports agree to facilitate.

The SESAR Concept of Operations (SESAR Consortium, 2013, 2007) highlights the importance of Strategic De-confliction in achieving the targets of increasing capacity and safety in Air Traffic Management (ATM) while improving flight efficiency, reducing costs and involving the AUs directly in the process by means of a Collaborative Flight Planning effort based on a dynamic rolling Network Operations Plan (NOP). This plan provides a common reference upon which the partners are able to optimize their business trajectories (EUROCONTROL 2012a, 2012b).

The term Strategic De-confliction is often used to define actions taken when the SBT takeoff time is known with sufficient accuracy (e.g., after *push-back*) or even after the flight is airborne but with sufficient time to allow a Collaborative Decision-Making (i.e., Collaborative Flight Planning) process to occur. This term excludes tactical instructions and clearances that require an immediate response but includes activities such as dynamic route allocation (SESAR Consortium, 2013, 2007).

The STREAM (*Strategic TRajectory de-confliction to Enable seamless Aircraft conflict Management*) project, launched under the auspices of SESAR WP-E [http://www.hala-sesar.net/stream] is aimed at developing innovative and computationally efficient Conflict Detection and Resolution (CD&R) algorithms for *strategic de-confliction* of thousands of trajectories within a few seconds or minutes by taking into consideration the AU preferences and network constraints. This system will enable air traffic to be de-conflicted over wide airspace regions and will permit large look-ahead times on the order of hours (e.g., 2 to 3 hours). The principal scope for application is represented by the European airspace, which falls under the responsibility of a single European Network Manager (NM) for coordination and optimization of air traffic flows. The developed algorithms can contribute to the achievement of the NM's goals by suggesting de-conflicted trajectories that closely match the AU preferences in a free-route environment, i.e., unconstrained by pre-structured routes, as is the practice today.

For the conflict resolution maneuvers to be effective, the complex interactions and emergent dynamics among the trajectories must be taken into account in a global scope because the resolution of one conflict may imply the reactive creation of a new conflict in the network (i.e., domino effects). Due to the high degree of connectivity in the European ATM Network, it is expected that only consideration of the entire European Airspace (i.e., global scope) at the micro level can ensure that all potential interactions are identified and that the final route allocation is globally de-conflicted at the strategic/planning phase under a collaborative optimization approach. Conflict resolution with a global optimization scope represents a highly combinatorial problem that has been considered to be untreatable (i.e., non-polynomial). Therefore, the use of classical optimization techniques, analytical methods or exhaustive combinatorial exploration of the solution space do not constitute practical methods for identifying conflict-free optimal solutions (Durand, N. et al., 1995).

Causal models can be employed as a fundamental component of a CD&R platform to assess and understand the emergent dynamics that a CR process can generate while considerably reducing the complexity and solution space of the problem. The advantage of causal models is that they are able to perform (using formal methods) an analysis of state-space (SS) to explore the dynamic evolution of a system and subsequently determine all possible future states that are *reachable given the specification of certain initial conditions*. The *state* of a dynamic system is the minimum amount of variables (known as *state variables*) for which knowledge of the current value of those variables and the future inputs to the system makes it possible to completely determine the evolution and values of the future states reached by the system (K. Ogata, 1995). The evolution of the system through different possible states can be graphically represented by the *reachability tree*, which opens a branch for each of the different possible state evolution starting from a previously known state (probabilistic/stochastic future states also can be supported to manage uncertainty). The *final states* are found at the end of each branch; a subset could be *feasible solutions* belonging to the *solution space* of the system and others are *non-feasible* final states.

A causal model used in the CD&R approach proposed by STREAM is introduced in this paper. The representation of the conflict resolution problem by causal modeling presents a better understanding of the upstream/downstream network effects implied in choosing a specific local resolution trajectory to solve a conflict. As a consequence, the solution space search can be reduced to a computer-manageable set of states, and flexible search methods can be applied to address the different multi-criteria definitions of global optimality. The proposed CD&R system takes into account several *locally optimal* (i.e., user preferred) resolution trajectories per each conflict detected and applies causal model post-processing to determine several conflict-free network solutions (i.e., final states). This goal is achieved via a causal analysis of the emergent dynamics (i.e., network interactions or "domino effects"). After the causal analysis, a single-solution scenario could be chosen (not tackled in this paper) by computing a global (multi-criteria) optimization function (e.g., efficiency, robustness, safety, equity, fairness, etc.) that is commonly agreed upon by the NM and the Airspace Users (AUs). Thus, the AU preferences are considered during both the generation of locally optimal trajectories and during the global optimization processes. This strategic CD&R approach implies an important paradigm change towards the automation of network and airspace management that will contribute to achieving the desired gains in capacity, safety and efficiency of the European ATM.

This paper is structured as follows. Sections 2 and 3 summarize the state of the art and the main key features of the STREAM CD&R architecture for establishing the applicable framework. Section 4 introduces the details of the causal model used to identify the global CD&R solutions. Finally, Section 5 presents the preliminary results obtained via simulation experiments, and Sections 6 and 7 outline the limitations, conclusions and future research.

2. LITERATURE REVIEW

Conflict Detection (CD) and Conflict Resolution (CR) systems can be classified according to the manner in which they handle detection/resolution when multiple conflicts arise among two or more trajectories. When the algorithms sequentially detect and solve the conflict by considering the minimum safety distances between each pair of trajectories without concern for the other trajectories in the network, they are based on a *pairwise strategy*. In contrast, if the entire traffic situation is examined simultaneously, they are based on a *global strategy* (James K. Kuchar and Lee C. Yang, 2000).

Currently, most CD algorithms implemented in operational applications (CTAS, FASTI, iFACTS, ERATO or VAFORIT, among others) are primarily based on pairwise strategies (EUROCONTROL, 2002, 2007, 2010a). Several automated CR tools are currently under development, and early operational applications are also based on pairwise strategies (James K. Kuchar and Lee C. Yang, 2000; M. Kupfer et al., 2008). This situation implies that Conflict Detection and Resolution (CD&R) is currently executed only at a local airspace-sector level, with a look-ahead time typically limited to a maximum of 20 minutes (i.e., tactical applications) and lacking a global perspective on how the decisions made at the local level will affect the rest of the network. An interesting academic approach (i.e., non-operational) for en-route conflict resolution with global optimization using genetic algorithms was presented previously (Durand, N. et al., 1995).

A global CD&R perspective is required for optimal de-confliction of the air traffic network. A resolution trajectory generated for solving a conflict between two trajectories could generate new interactions (i.e., *downstream conflicts*) that previously did not exist in the network. Additionally, a resolution maneuver could solve the original downstream conflicts that existed previously in the original trajectory. These new interactions that appear in the network (or the elimination of pre-existing interactions) are known as "domino effects" or more formally as *network effects* (K. D. Bilimoria et al., 2000). When a trial resolution trajectory generates new network interactions, this is referred to as a *destabilizing effect* (i.e., negative), whereas a *stabilizing effect* (i.e., positive) occurs when one local conflict resolution indirectly solves one or more downstream conflicts. In (J. Krozel et al., 2001), the authors underline the importance of taking into consideration these domino effects in the design of a CR system because these phenomena notably affect the quality of the resolutions from the network point of view and are thus a necessary condition for the adoption of an effective global strategy in the CD&R system for providing optimal conflict-free network solutions.

(Durand, N. et al., 1995) argued that the complexity of conflict resolution with global optimization for n aircraft is a Non-deterministic Polynomial (NP) combinatorial problem with $2^{\frac{n(n+1)}{2}}$ possible solutions. Due to such a huge solution space, no efficient analytical mathematical solution is known for finding optimal global solutions. In (Durand, N. et al., 1995), several conflict resolution models were analyzed (analytical, reactive, priority-rules based…) by pointing out the shortcomings of the final solutions, which generally do not achieve global optimization when considering conflicts among $n > 2$ aircraft. Genetic algorithms were introduced as a stochastic optimization method to achieve global (near-)optimal solutions for highly combinatorial CR problems by generating random feasible solutions that are iteratively improved by selection, crossover and mutation methods until several feasible solutions are achieved. Later, a local search via a hill-climbing algorithm selects the best scenario according to the given metrics (e.g., minimum delay).

Similar to genetic algorithms, causal models also can be applied for solving global (highly) combinatorial optimization problems. The advantage of causal models is that rather than selecting random solutions that best fit a particular optimization function, the resulting solutions are obtained through representation and propagation of the underlying cause-effect relationships between the individual components (i.e., the intended trajectories) that compose the complex system, thus allowing for a better understanding of the complex system as well as the identification of those trajectories that have a greater impact on the network. Causal models specified in the Colored Petri Nets (CPN) formalism have been successfully applied to implement CR algorithms for Terminal Maneuvering Areas (TMA) (Zúñiga et al., 2010).

Free route operations will imply the relaxation of structured routing constraints for flights, further implying the possibility for the Airspace Users to plan their trajectories freely between a defined entry point and a defined exit point of the free route airspace with the possibility of deviating via intermediate navigation points without reference to the fixed route structure. Within the free route airspace, flights remain subject to air traffic control at all times and to any overriding airspace restrictions (SESAR Consortium, 2008, 2012). After a certain level of strategic conflict management and traffic synchronization, the final RBT may include pre-de-conflicted 3D routes subject to dynamic refinement or adjustment during flight. This situation constitutes a quantum leap with respect to the current airspace structure, which consists of a set of predefined airways that depend on a ground-based infrastructure of navigation aids and rely on the subdivision of the airspace into ATC sectors aimed at facilitating the management of flights. The introduction of modern communication, navigation and surveillance technologies combined with the development of specific ATM procedures is intended to provide traffic managers with a greater degree of flexibility in dynamically reconfiguring airspace to adapt to changing conditions (e.g., convective weather disruptions, Flexible Use of Airspace or any other unforeseen event) and to user-preferred routing (Zelinski and Jastrzebski, 2012; Kopardekar et al., 2007).

Uncertainty is a major issue affecting CD&R systems, especially if trajectories at the strategic level are considered. In (Durand, N. et al., 1995), speed uncertainties are identified as the most important factor affecting the robustness of the CD&R solutions. However, with the introduction of a 4D-Flight Management System (4D-FMS, which is currently spreading rapidly among airlines), the control and guidance of an aircraft are becoming increasingly accurate, thus reducing this uncertainty. According to (Zelinski and Jastrzebski, 2012), convective weather is currently identified as one of the factors that most seriously affect the network route structure, thus requiring real-time algorithms to reconfigure the airspace. Other sources of uncertainty should be considered, e.g., navigational errors, tracking errors and deviation risk (Ruiz et al., 2012a). In this paper, a simplified 4D nominal model is presented (i.e., without considering weather perturbations, contingency events or other sources of uncertainties), and different sources of uncertainties could be supported by the model design.

3. STREAM APPROACH

3.1. Concept of operations

Relying on the SBT/RBT and Strategic De-confliction SESAR concepts and on the assumption of the general availability of a 4D-FMS navigation system, the STREAM solution adopts a combination of different resolution strategies (route, speed and flight-level modifications) that will be applied to de-conflict the involved SBTs at a strategic level by taking into account the characterization of the conflict (i.e., type, location and duration) and the preferences of the Airspace Users (EUROCONTROL, 2012c, 2013; Ranieri et al., 2011).

The idea is to capitalize on the availability of the 4D trajectory information available prior to takeoff (i.e., SBT) or actual flight (i.e., RBT) with the highest possible accuracy depending on the planning horizon. The analysis of this information will allow the Network Manager, in close cooperation with the Local Traffic Managers and the Airspace Users, to build an "uncertainty 4D tube" around each nominally predicted trajectory to create a picture of the traffic evolution that is robust to different sources of uncertainty (e.g., navigation and tracking errors, tactical delays, risk of trajectory deviation, etc.). Unexpected events such as trajectory deviations that require tactical interventions could still occur, and thus the ATC Officer (ATCO) clearances will continue to be necessary. However, the overall predictability of the system will be enhanced, thus implying fewer tactical interventions and more stable plans.

The presence of convective weather (e.g., thunderstorms) or other sources of uncertainty with deep impacts on the strategically generated plans will be addressed via a real-time reconfiguration of the routes allocated to each flight. The information on flight intentions and on the current and forecasted status of the entire European network will be available through the NOP, a continuously updated rolling plan that enables a seamless conflict management process running continuously from the strategic phase (pre-departure, collaborative design of the NOP) up to the execution phase (automation-assisted, controller-driven conflict resolution).

A typical scenario at the European level with a planning horizon of 2-3 hours is expected to include up to 5000 simultaneously active flights (Ranieri et al., 2011). The high density and complexity of European air traffic implies a high number of interactions among the different trajectories, especially in those regions that are expected to be more congested. Thus, high computational efficiency is required in the CD&R algorithms for storing and analyzing the state-space information of several thousands of trajectories to ensure that the proposed local resolutions do not generate secondary reactive conflicts in other zones of the network.

After the CD&R process, different conflict-free solution scenarios will be generated. Each of these feasible scenarios will be weighted according to different performance indicators for efficiency, robustness, fairness and equity (EUROCONTROL, 2012c, 2013; Ranieri et al., 2011). Under all circumstances, a final agreement between the involved service providers and the impacted Airspace Users will be necessary to close the SBT negotiation and implement a RBT for each flight. Thus, during the negotiation process, the Airspace Users may express their preferences according to their business targets, which will be used to identify the most beneficial global solution according to selected commonly agreed metrics, thus formally realizing a multi-criteria global optimization of the network route-structure allocation.

For simplicity purposes, the STREAM concept of operations only considers en-route traffic (i.e., from Top of Climb (ToC) to Top of Descent (ToD)), and Direct Routes are applied as a simplification of the Free-Routing concept.

3.2. Uncertainty

Several sources of uncertainty have been addressed in the framework of the STREAM project. The uncertainty related to navigational imprecision and tracking errors could be tackled by adding uncertainty buffers to the SBTs/RBTs, whose final result can be treated as 4D corridors in which aircraft can execute their flights within a high confidence interval (4D-FMS navigation assumed).

Unexpected events (i.e., perturbations) can still occur, thus requiring a modification of the NOP. In this paper, the perturbations are classified as:

Individual-level perturbations, referring to those unexpected events caused by the AUs that generally affect only a reduced set of trajectories, e.g., large delays and/or trajectory deviations outside of the uncertainty buffer.

Network-level perturbations, referring to those perturbations that are independent from the behavior of the AUs and generally affect a large set of trajectories or even the entire network, e.g., convective weather and volcanic ash, among others.

The problem of how to address individual-level perturbations is a complex topic that is not covered in this paper. However, in general, these issues can be addressed by first identifying the AUs responsible for the produced deviation and forcing them to correct the deviation by applying tactical amendments (the same automated STREAM CD&R algorithms could be adapted to tactical operations) according to the principle of "*the one that deviates is the one that pays*".

In case of network-level perturbations, such as a dangerous storm that forces the NM to close certain (demanded) airspace sectors, the complete network route allocation must be reconsidered. Again, the AUs may provide the NM with their preferred SBTs/RBTs by considering the most updated information on the state of the network. If the CD&R tools applied are sufficiently rapid, then the NM can provide a new airspace configuration/route allocation adapted to the AU preferences that is subject to the changing network restrictions in real-time (Ruiz, S. and Piera, M., 2013). According to STREAM ConOps, an acceptable look-ahead time horizon for the NOP would be approximately 2 hours and the updating frequency less than a minute.

3.3. System architecture

The system architecture developed in the STREAM project is illustrated in Fig. 1. The inputs of the system are a set of SBTs/RBTs published by the airlines as well as selected extra information on the current state of the ATM, e.g., airspace availability and configuration. The relevant subsystems consist of:

A *Conflict Detection* (CD) module that analyzes the different trajectories using a *Spatial Data Structure* (SDS) with a twofold purpose:

a. to generate the state-space representation of the network and
b. to perform conflict detection.

A *Resolution Trajectory Generator* (RTG) module that solves the conflicts by generating different alternate trajectories (using different types of maneuvers for each aircraft and conflict) with a local optimization scope. Each newly generated trajectory is sent back to the CD module and stored in the SDS to generate and store the new state-space information.

An *Interaction Causal Solver* (ICS) that is tasked with analyzing the state-space stored in the SDS (with the original and alternate resolution trajectories) to detect network interactions (i.e., positive or negative domino effects) among all of the processed trajectories and to subsequently propose several conflict-free scenarios at the network level. Post-processing applies metrics to the available feasible solutions and can be conducted to obtain the globally optimal solution scenario.

A communication interface used to coordinate the CD, RTG and ICS modules.

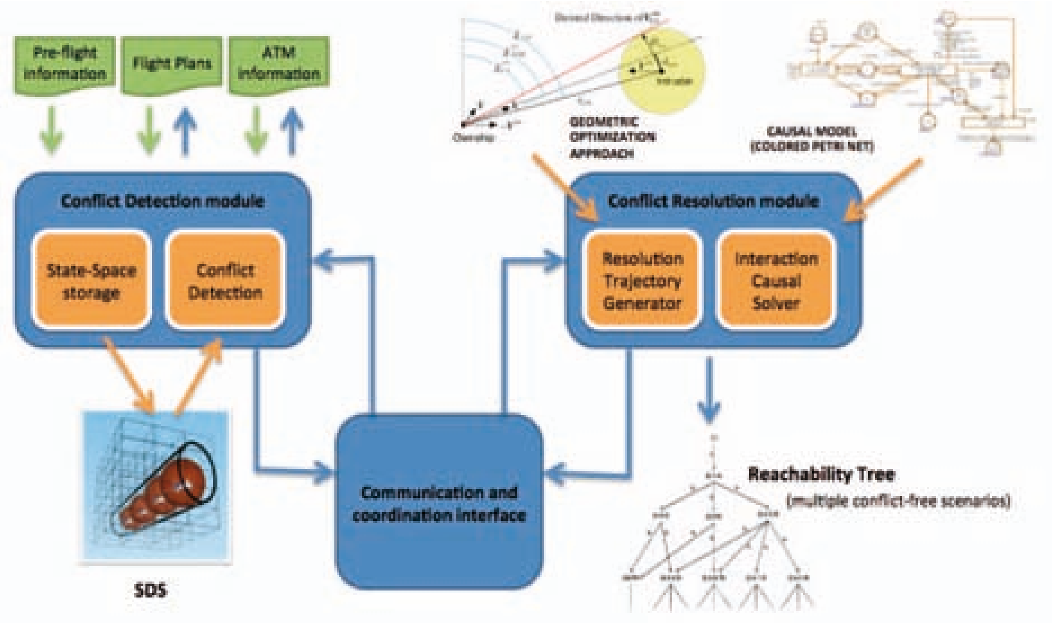


Figure 1. STREAM system architecture

The Spatial Data Structure (SDS) is a database that represents a spatial region (e.g., an airspace or air sector) using individual memory positions to represent each of the discrete (3D) coordinates of the sector. Such memory positions are sorted such that given a certain coordinate, the information stored inside the SDS (associated with such a coordinate) is easily recoverable by applying linear functions (Sergio Ruiz and Miquel A. Piera, 2009, 2010). The SDS can be treated as a mesh of discrete points distributed throughout the space region that is considered by the conflict detection process, as conceptually represented in Fig. 2.

Spatial Data Structures have been explored under the STREAM project as a technique for implementing the CD process with excellent results in terms of time performance due to the linear computational complexity (denoted by O(n)) of the CD algorithms based on SDS (Ruiz, S. and Piera, M., 2013; Ruiz et al., 2012a, 2012b, 2011). In addition, the use of SDS allows storage of the entire state-space description of the traffic among all of the processed trajectories at the time when the conflict detection analysis is performed. Causal models can be employed based on the SS information stored in the SDS because all of the processed trajectories (both planned and alternate “what-if” types of trajectories) will remain stored as a “4D snapshot” of the ATM system (Ruiz, S. and Piera, M., 2013; Ruiz et al., 2012b)

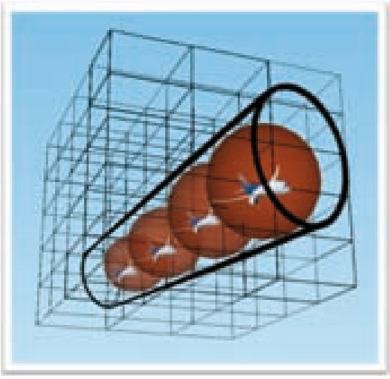


Figure 2. SDS conceptual representation

The main purpose of the RTG module is to compute new optimal alternate trajectories for each aircraft in conflict (using different maneuvers in response to a particular conflict/network restriction). The RTG module could therefore support the AU participation in defining their preferred alternate flight plans in response to a set of restrictions and types of maneuvers (i.e., turn left, turn right, increase flight level, decrease flight level, speed up, speed down, or a combination of these) imposed by the NM to solve a particular detected conflict. Thus, each new resolution/alternate trajectory generated by the RTG must be considered locally optimal given a particular set of network restrictions and maneuvers. The ICS module takes advantage of such user preferences/local optimality of the resolution/alternate trajectories to reduce the solution space search and therefore to find globally optimal solutions. For simplicity, the generation of these resolution trajectories in STREAM is based on a Geometric Optimization Approach (GOA) (Bilimoria, 2000; Geser, A. and Munoz, C., 2002). This technique allows resolution of the conflicts by applying different types of maneuvers, i.e., Heading Changes, Speed Changes, Level Changes or a combination. Time restrictions (e.g., Requested/Controlled Time of Arrival) can also be introduced in the GOA algorithms (Bilimoria and Lee, 2002). These resolutions based on GOA are referred to as “optimal” in the sense that they minimize the velocity vector changes with respect to the original trajectory. Other approaches to obtaining optimal/user-preferred resolution trajectories also could be compatible with the STREAM concept, such as using more complex and advanced resolution algorithms that better exploit the concept of free routing (e.g., taking advantage of favorable wind flows, minimizing en-route charges, among others) and a more complete set of restrictions (e.g., aircraft performance limits, fuel capacity limits, airspace/sectors availability, etc.) (EUROCONTROL 2012c, 2013; Ruiz et al., 2012b). Notably, the RTG internal logic is independent of and transparent to both the CD and ICS modules. It should also be recognized that cooperative resolutions could be accepted because the STREAM solution operates at a strategic/pre-tactical level to generate a dynamic route allocation for the European ATM.

In the ICS module, a CPN-based causal model is applied to take into consideration the downstream effects of these resolution amendments by exploring the SS information stored in the SDS (both first-planned and potential/alternate types of trajectories are stored). The amended trajectories are analyzed to detect possible new conflicts (i.e., destabilizing interactions) with the remainder of the traffic on the network or to detect the indirect resolution of previous downstream conflicts (i.e., stabilizing network effects). After one (or several) feedback cycle(s) in which the CD module processes the CR proposed amended trajectories and returns the new generated conflicts, the CR again takes the updated information from the SDS and, via causal analysis, finds and finally delivers several conflict-free scenarios (i.e., feasible final states) that can be compared and assessed by an integrated Decision Support Tool (supervised by human operator) to determine the preferred option for enforcement.

3.4. System logical functionality

The system architecture presented in the previous section is applied according to the following steps:

0. A set of user-preferred free-route trajectories is introduced into the CD&R system.
1. Given a set of trajectories, the CD module detects the conflicts among them. All of the processed trajectories remain stored in the SDS to ease the detection of conflicts among new sets of trajectories and their interactions with previously processed sets.
2. The RTG module generates several locally optimal trajectories per each pair of trajectories and conflicts by considering different restrictions, i.e., different types of maneuvers used to solve single conflicts, multiple conflicts, to match time-restrictions or to find cooperative resolutions, among others. The *local optimality* of the trajectories is defined by the AUs, who express (directly or indirectly) their preferred alternate SBTs/RBTs for each flight given a set of restrictions provided by the NM through the CD module. Note that the order of conflict processing does not affect the local optimality of the alternate SBTs/RBTs because each pair of trajectories in the conflict are processed at this step and treated as totally isolated in the network, i.e., the optimal AU (local) resolutions are generated with no consideration of other potential interactions with the rest of the trajectories.
3. The CD module again evaluates the new set of alternate SBTs/RBTs to detect conflicts among them as well as with the previously processed sets of trajectories. The conflicts detected among different alternate SBTs/RBTs generated for the same flight are discarded (an aircraft will only fly one of its alternate SBTs/RBTs so they cannot be in conflict among themselves).
4. Points 1, 2 and 3 described above constitute a cycle that can be repeated several times to detect and provide resolution SBTs/RBTs to secondary and tertiary emergent conflicts, thus increasing the probabilities of finding final feasible solutions. At the end of this step, a complete 4D representation of the airspace’s present and future (expected) states remains stored in the SDS.

5. All of the alternate SBTs/RBTs generated at point 2 per each flight are sorted according to a given order of preference expressed (directly or through agreed indirect methods) by the AUs. The information taken from the AU preferences will avoid exploration of sub-optimal feasible solutions, thus reducing the exploration of the solution space to the set of *Pareto-efficient feasible solutions*.
6. Causal exploration with constraint propagation involves the following process. The causal model consists of opening a branch of the reachability tree per each SBTs/RBTs and subsequently propagating the constraints by activating/deactivating the set of primary, secondary or tertiary conflicts (extracted from the SDS at step 4) and the availability of the pre-sorted alternate SBTs/RBTs (introduced as input in step 0 or generated by the RTG at step 2). This model takes into consideration all of the possible emergent dynamics (i.e., domino effects), thus achieving *completeness* of the solution space, and at the same time, *reducing the solution space* exploration by focusing on the Pareto frontier of the feasible set of solutions.
7. The computation of online metrics (of efficiency or any other criteria) during the causal exploration and their comparison among the branches that belong to the same level of the reachability tree allows a *driven search* via a hill-climbing/minimal-gradient algorithm, which outputs the feasible final states with better metrics first (i.e., more efficient scenarios are found first).

Note that the order in which conflicts are processed and locally solved by the RTG module (step 2) does not affect the ICS causal analysis used to find global conflict-free solutions (step 6 and 7) because the ICS analyzes the overall 4D state-space information stored in the SDS once the CD-RTG-CD sequence (steps 1, 2 and 3) has halted after a (parameterizable) maximum number of cycles (step 4).

4. CAUSAL MODEL: INTERACTION CAUSAL SOLVER

4.1. Emergent dynamics in conflict resolution

A maneuver that is intended to solve a conflict can generate other conflicts that previously did not exist in the network (i.e., emergent dynamics). These network effects are referred to as *interactions* and can be classified as follows (see Fig. 3):

Primary conflict: A conflict between two original SBTs/RBTs

Secondary conflict: A conflict that emerges between a resolution maneuver proposed by the CR to solve the primary conflict and the surrounding original SBT/RBT.

Tertiary conflict: A conflict that emerges between two resolution maneuvers belonging to any surrounding aircraft.

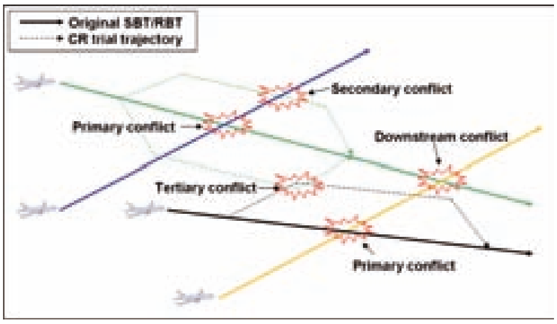


Figure 3. Interactions among SBTs/RBTs and CR trial trajectories

Consider the example illustrated in Fig. 4(a) in which a scenario with three trajectories, i.e., Tr1, Tr2 and Tr3, occurs with a conflict between Tr1 and Tr2.

For reasons of simplicity, only one resolution trajectory is considered and calculated for each aircraft in conflict. Thus, the conflict in Fig. 4(b) is solved by proposing Tr11 (which has a resolution cost of C=1) as a substitute for Tr1. However, a new secondary conflict subsequently emerges between Tr11 and Tr3. In this case, because the original trajectory Tr1 is not in conflict with Tr3, the new trajectory Tr11 causes a negative domino effect (i.e., a destabilizing network effect).

In contrast, the conflict in scenario (a) can also be solved by exchanging Tr2 with Tr21, as represented in scenario (c), with a resolution cost of C=1. Due to the presence of the secondary conflict that arises in (b), two new scenarios are explored. In (d), trajectory Tr11 is substituted by Tr111, which has a cost of C=1.5 with respect to the original trajectory Tr1. Alternatively, in scenario (e), Tr3 is substituted by Tr31 to avoid the network interaction that emerges as a consequence of solving the conflict in scenario (a). Trajectory Tr31 has a cost C=1, which together with the cost of Tr11 results in a total resolution cost of C=2.

Note that three alternative feasible conflict-free scenarios are proposed from the unique conflict given in scenario (a). Because certain scenarios have been generated due to the emerged domino effects during the resolution trajectory generations (scenarios (d) and (e)), the decision-making process used to select one of the available conflict-free scenarios will also (implicitly) take into account the domino effects. In this example, if the criterion for selection is the minimum total cost, then the *best* scenario is (c) because it implies the lowest costs. However, other metrics may be considered for the selection of the *optimal* or *globally preferred* scenario, such as safety, robustness, equity, and fairness, among others (i.e., multi-criteria optimization) (EUROCONTROL, 2012c, 2013; Ranieri et al, 2011).

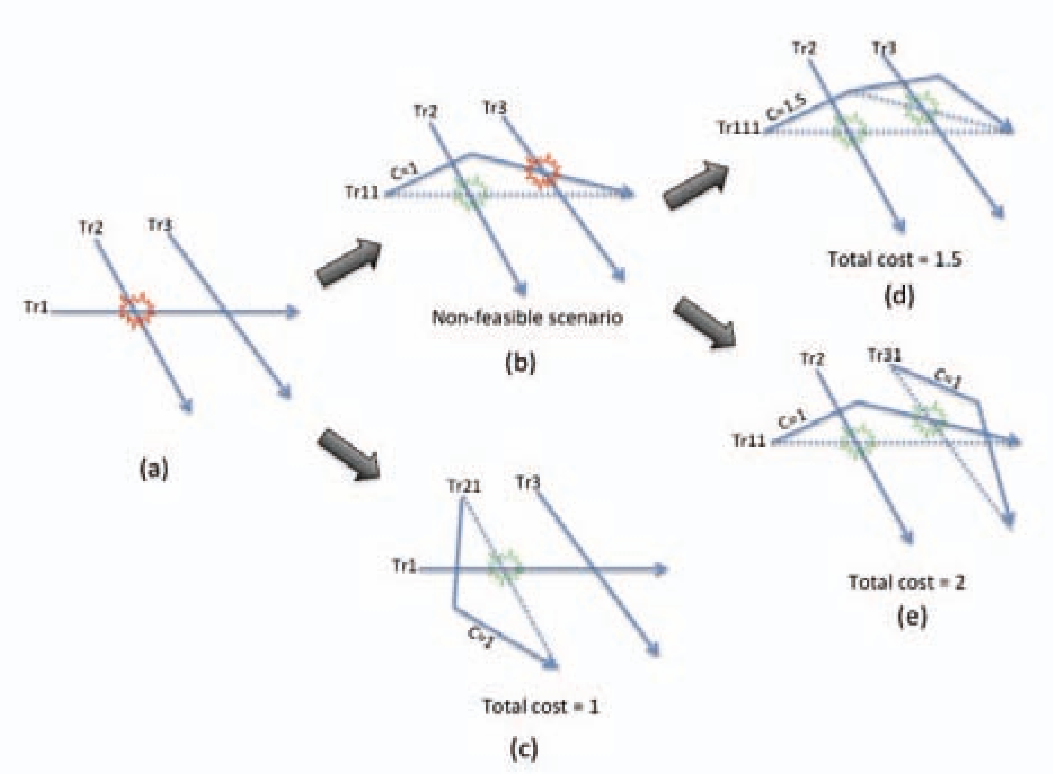


Figure 4: Different scenarios generated as a resolution for one primary conflict

The example illustrated in Fig. 5 represents a more complex situation that introduces two aspects: the effects of tertiary conflicts and how metrics other than cost may provide useful information for making better decisions at the network level. Note that this example consists of an original scenario (a) with five trajectories, namely, Tr1, Tr2 and Tr3, which are exactly the same as in the previous example (and thus, create a conflict between Tr1 and Tr2), with the addition of Tr4 and Tr5, which have been added to increase the complexity of the scenario. Note that Tr4 and Tr5 are in conflict and thus two conflicts exist in the original scenario.

Let us assume that from the ATC point of view, the preferred solution for solving the conflict between Tr4 and Tr5 is to apply trajectory Tr41 instead of Tr4. Nevertheless, two options are considered to solve the conflict between Tr1 and Tr2. Note that scenario (b), which applies trajectory Tr11, again generates a secondary conflict with Tr3. Thus, two new scenarios are considered, (d) and (e), with both acting as feasible conflict-free solutions with total costs of C=2.5 and C=3, respectively. However, scenario (c) generates a tertiary conflict between Tr21 and Tr41. In this case, a new scenario (f) is generated using Tr51 to solve the conflict instead of Tr41, even if it is known that resolution with Tr51 is sub-optimal compared with the Tr41 resolution. In this case, this new scenario (f) leads to another feasible conflict-free scenario. Note that in this example, it is not clear which of the feasible scenarios is the *best* one, even if only the cost criterion is taken into consideration during the decision-making process because scenarios (d) and (f) display the same total resolution cost of C=2.5. In addition, note that, depending on the policies of the NM, even scenario (e) could be considered as the best solution because according to the equity and fairness criteria, this scenario seems to share the resolution costs among all agents in a manner that is more fair (i.e., all individual resolution costs are equal to C=1).

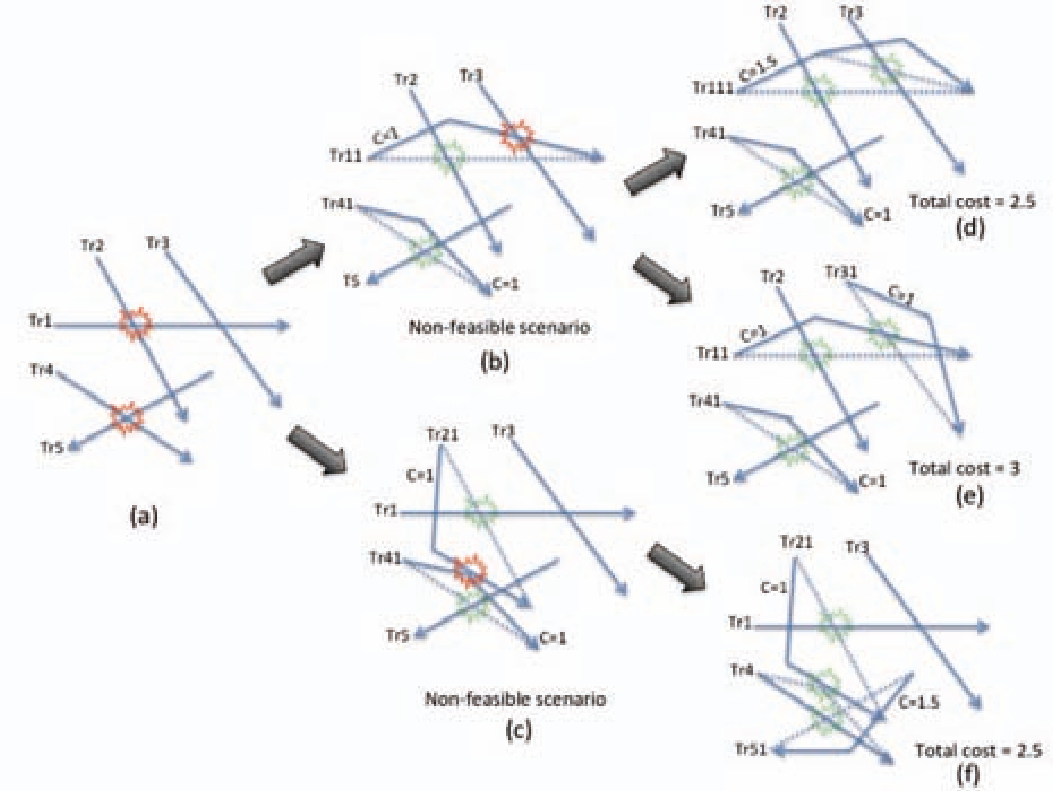


Figure 5: Different scenarios generated as a resolution to two primary conflicts

Due to the underlying system-emergent dynamics, conflict resolution for *n* aircraft with a global scope (i.e., taking into account the emergent dynamics) is a highly combinatorial problem in which the direct exploration of *all* feasible solutions for global optimization purposes is not feasible. Causal models can contribute to reducing the size of the problem and provide (near) optimal solutions.

4.2. Causal algorithm

A causal approach makes it possible to represent and analyze the events occurring within a dynamic system (in this case, the network interactions) as well as their logical sequence of occurrence. The core concept of the model presented in this paper is to assign *one conflict-free trajectory per aircraft* at each feasible solution. Because different alternate trajectories will exist for each aircraft in conflict, there will also be many combinations that lead to several feasible conflict-free solutions. To find these feasible solutions, the algorithm uses the information on the interactions (i.e., conflicts) detected by the SDS-based CD algorithm and the information on the alternate and original trajectories generated by the RTG (note that each of the trajectories generated by the RTG solves at least one conflict in the network).

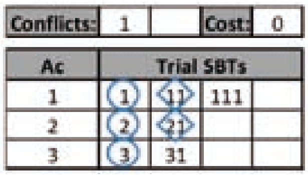
The state of the system (i.e., minimal information needed to solve the problem) can be described by the following:

Active SBTs/RBTs: Trajectories actually assigned to each of the aircraft/flights. Active SBTs/RBTs are represented with circles in Fig. 6 (trajectories #1, #2 and #3 are active in the figure).

Active conflicts: Conflicts (if any) actually affecting the feasibility of the solution. Active conflicts are updated in the list of conflicts in Fig. 6 (conflict #1 is active, as shown in the cells attached to the field “Conflicts”).

Active trial resolution trajectories: A set of trial trajectories that are generated to solve at least one of the active conflicts (sorted from most to least preferred according to the AU criteria). Active resolution SBTs/RBTs are represented by 45-degree phased squares in Fig. 6 (trajectories #11 and #21 are active to solve conflict #1; trajectories #111 and #31 are inactive because they solve other conflicts but not conflict #1).

Accumulated total cost: Aggregated sum of the individual costs of the resolution trajectories with respect to the original SBTs/RBTs. The cost is updated in the corresponding field of Fig. 6 (cost is 0 for the state shown).



Conflicts:	1		Cost:	0

Ac	Trial SBTs			
1	1	11	111	
2	2	21		
3	3	31		

Figure 6: State description of the causal model

The causal exploration can be summarized in the following steps:

1. Per each active conflict, identify and activate *all* trial trajectories generated by the RTG to solve that conflict.
2. Per each active conflict, open two branches: one branch per each aircraft involved in the conflict.
3. At each of the branches, deactivate the SBT/RBT assigned to the aircraft in conflict and propose one of the locally optimal resolution trajectories from those activated in step 1 (taking the most preferred for the AUs first, regardless of the type of maneuver to execute, e.g., turn right, turn left, change speed, flight-level change or any combination of them).
4. Update the cumulated total cost of the scenario according to the chosen efficiency metrics (e.g., fuel cost).
5. Update the list of active/inactive conflicts

The termination condition (i.e., final state) is defined by two different states:

a) There are *no active conflicts*, which means that the causal exploration has reached a *feasible solution*.

b) There are *no more active trial trajectories* available to solve a given active conflict, which means that a *non-feasible* final state has been reached.

At the end of the process, several combinations of conflict-free solutions are delivered (if any exist). By computing different metrics to measure efficiency, safety, robustness, equity and fairness of the solutions (among other criteria), it should be possible to determine which of the feasible conflict-free solutions delivered after the causal analysis is the most preferred for the airspace stakeholders, including the AUs, ANSPs and NM (given a commonly agreed upon objective function) (EUROCONTROL, 2012c, 2013; Ranieri et al, 2011).

4.3. Examples

4.3.1. Scenario 1: Cause-effects relationships and solution space reduction

Let us solve the example presented in Fig. 4 using the above causal algorithm and based on the state representation shown above (Fig. 6). Fig. 7 illustrates the reachability tree after the causal analysis. Note that the restrictions include a primary conflict (conflict #1) and a secondary conflict (conflict #2). Also note that the information on the trial trajectories includes the conflict that is solved (i.e., the RTG used the indicated conflict to generate a locally optimal resolution trajectory) and the cost of the resolution with respect to the original trajectory. The associated conflicts and costs of the original trajectories are set to zero because they are considered to be the user-preferred optimal trajectories and were not generated to solve any conflict.

Each of the states corresponds to one of the states of Fig. 4. This correspondence is indicated with a letter over each single-state description boxes.

Each branch opened for the causal exploration contains associated extra information to ease the visual inspection of the scenario: two numbers separated by a colon, which indicates the conflict that is solved (first number) and the trajectory involved in the conflict that is substituted (second number), e.g., the branch 1:2 indicates that the state is changed to solve conflict #1 by deactivating trajectory #2 and proposing one of the active alternate trajectories generated by the RTG to solve conflict #1.

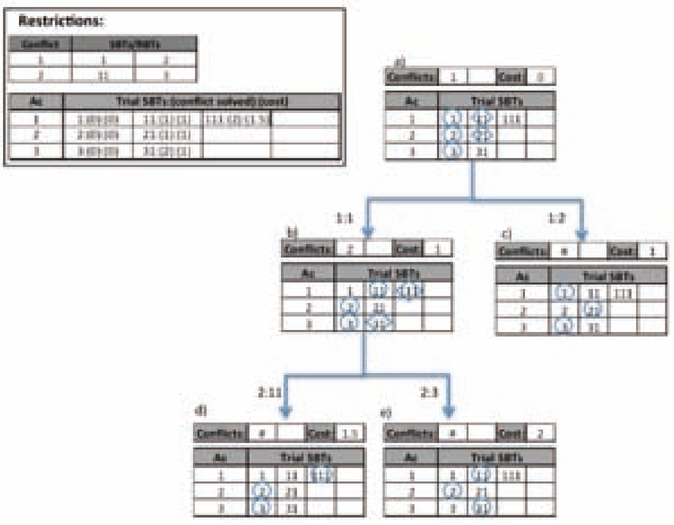


Figure 7: Reachability tree of Scenario #1 presented in Fig. 4

According to Fig. 7, Scenario #1 has three different feasible solutions (the absence of conflicts is represented by the symbol # in the corresponding feasible solution states). Note that the causal model with constraint propagation has avoided the naive combination of all trajectories, thus notably reducing the solution space search.

In Scenario #1, two resolution trajectories (i.e., Tr111 and Tr31 of Fig. 4) were generated to solve a secondary conflict (i.e., conflict #2), which implies that the cyclic interaction CD-RTG-CD was run twice (see point 4 of Section 3.4: System logical functionality). If this cyclic interaction were run only once, conflict #2 would still be present but not resolution trajectories Tr111 and Tr31. Thus, only two final states would be present in Fig. 7, state (*b)* (non-feasible scenario) and state (*c)* (feasible solution). Therefore, by increasing the number of CD-RTG-CD cyclic interactions, it is possible to provide resolutions and state-space information for secondary, tertiary or *n*-order conflicts and to increase the probability of finding conflict-free solutions. In addition, this process increases the solution space that must be analyzed (note that a pre-determined maximum number of CD-RTG-CD cycles must be considered to avoid potential infinite loops).

4.3.2. Scenario 2: Several trials per conflict and Pareto-frontier solution space

In general, the higher the number of resolution trajectories generated at the local level (i.e., different trajectories that solve the same conflict between two aircraft), the higher the probability of finding a global feasible solution (i.e., solving all the conflicts of the scenario at the network level) because the amount of final states as well as their associated probability of being feasible solutions is also increased.

Intuitively, note that a flight-level change resolution maneuver could be sub-optimal from a fuel-consumption point of view if compared with a heading change maneuver; however, if no feasible solution is found using heading changes, the flight-level maneuver may be a valid candidate for resolution. Thus, by increasing the amount of acceptable resolution maneuvers, one also increases the probability of finding a network-conflict-free feasible solution. Additionally, note that a flight-level change may reduce the complexity of the original flight level, and thus, in the case of highly complex scenarios, the flight-level change might constitute an optimal solution from the network point of view even if it is sub-optimal at the individual level.

Therefore, generating several different resolution trajectories offers additional flexibility for using the airspace capacity in a more efficient manner. Unfortunately, the decision-making process also becomes more complicated because additional flexibility implies analysis of a larger amount of information.

Fig. 8 illustrates a variation of Scenario #1 in which a higher number of trial trajectories has been added to solve the same conflict. The new trajectories are Tr12 for aircraft #1 and Tr22 for aircraft #2, which are generated to solve conflict #1 (with costs of 1.2. and 1.4, respectively), and Tr32 for aircraft #3, which is generated to solve conflict #2 (with a cost of 2).

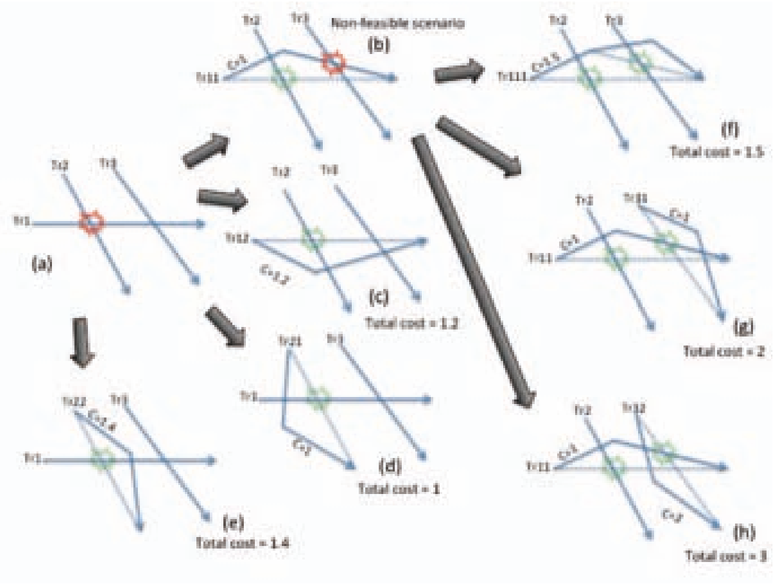
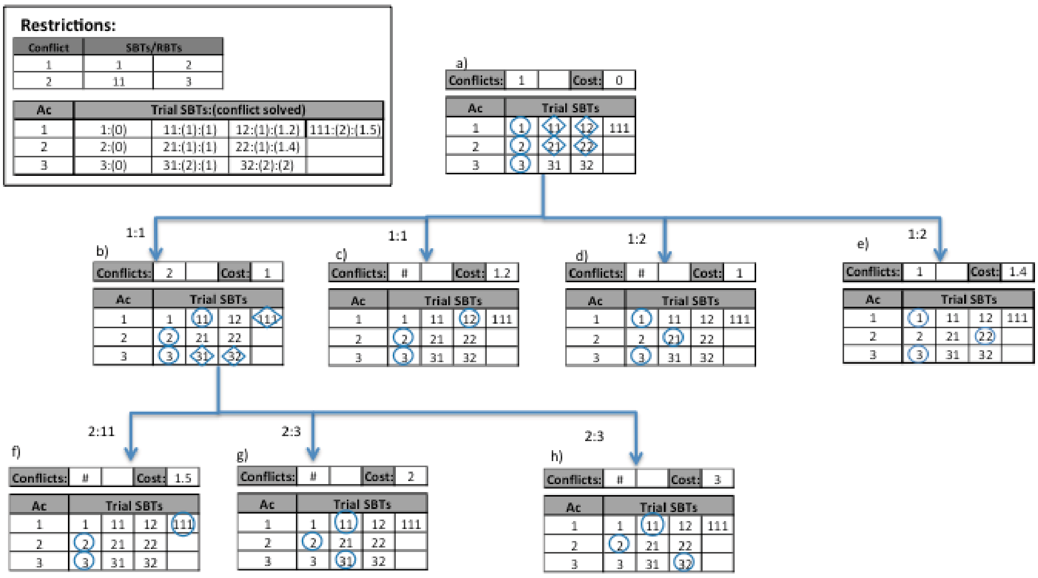


Figure 8: Scenario 2: Exploring the effects of adding several trials per conflict



Restrictions:

Conflict	SBTs/RBTs	
1	1	2
2	11	3

Ac	Trial SBTs:(conflict solved)			
1	1:(0)	11:(1):(1)	12:(1):(1.2)	111:(2):(1.5)
2	2:(0)	21:(1):(1)	22:(1):(1.4)	
3	3:(0)	31:(2):(1)	32:(2):(2)	

a)

Conflicts:	1		Cost:	0

Ac	Trial SBTs			
1	1	11	12	111
2	2	21	22	
3	3	31	32	

1:1

b)

Conflicts:	2		Cost:	1

Ac	Trial SBTs			
1	1	11	12	111
2	2	21	22	
3	3	31	32	

1:1

c)

Conflicts:	#		Cost:	1.2

Ac	Trial SBTs			
1	1	11	12	111
2	2	21	22	
3	3	31	32	

1:2

d)

Conflicts:	#		Cost:	1

Ac	Trial SBTs			
1	1	11	12	111
2	2	21	22	
3	3	31	32	

1:2

e)

Conflicts:	1		Cost:	1.4

Ac	Trial SBTs			
1	1	11	12	111
2	2	21	22	
3	3	31	32	

2:11

f)

Conflicts:	#		Cost:	1.5

Ac	Trial SBTs			
1	1	11	12	111
2	2	21	22	
3	3	31	32	

2:3

g)

Conflicts:	#		Cost:	2

Ac	Trial SBTs			
1	1	11	12	111
2	2	21	22	
3	3	31	32	

2:3

h)

Conflicts:	#		Cost:	3

Ac	Trial SBTs			
1	1	11	12	111
2	2	21	22	
3	3	31	32	

Figure 9: Reachability tree of Scenario #2 presented in Fig. 8

Fig. 9 shows the corresponding reachability tree for Scenario #2. Adding more resolution trajectories per conflict and aircraft has increased the amount of final states to six feasible solutions (i.e., states *c, d, e, f, g* and *h*), and thus, it can be observed that adding more flexibility to the original Scenario #1 increases the size of the SS to be analyzed.

Nevertheless, note that certain final states dominate over others. For instance, final state *d* is *strictly preferred* over final state *e* because, according to the preferences of aircraft #2, trajectory Tr21 (cost = 1) is preferred over Tr22 (cost = 1.4), whereas the rest of the trajectories remain constant in both states. It is said that a given solution is *Pareto-efficient* if any aircraft cannot improve its situation while the rest of trajectories remain static. In this case, state *d* is Pareto-efficient, whereas state *e* is not.

Note that different resolution trajectories that apply different maneuvers to solve the same conflict can be sorted according to the AU preferences. The causal model can take advantage of this information to reduce the solution space search and find the Pareto frontier.

The exploration of final states can be reduced to the Pareto frontier by assigning the best available option from the subset of activated resolution trajectories at each branch step. If the best option does not drive to a feasible solution, then the following available option is attempted. If no additional resolution trajectories are available and if active conflict still exists, then the final state is a non-feasible scenario (i.e., no solution is found during the exploration of this particular branch).

Applying these tree-exploration rules, only one branch in Fig. 9 would be opened for each pair of conflicting trajectories. In the case of branch 1:2, state *d* is explored first because Tr21 is the best option available at state *a* for aircraft #2. Because *d* is a feasible solution (i.e., no active conflicts), it is not necessary to explore state *e*. State *e* would be explored only if state *d* is not feasible.

Note that if aircraft #2 could use many different resolution trajectories to solve same conflict #1 (e.g., heading change, flight-level change, different speed profiles, etc.), then the amount of dominated states (i.e., non-Pareto) avoided during the causal exploration search would be considerable. However, the larger the amount of alternate trajectories is, the higher the probability of finding feasible solutions.

4.3.3. Scenario 3: Domino effects and completeness of the solution space

Consider a variation of Scenario #1 that includes a new conflict between trajectories Tr1 and Tr3. Fig. 10 graphically represents the solution space if conflict #1 is solved first, whereas Fig. 11 corresponds to the case in which conflict #2 is considered first. For simplicity, only one resolution trajectory is considered per each pair of conflicting trajectories.

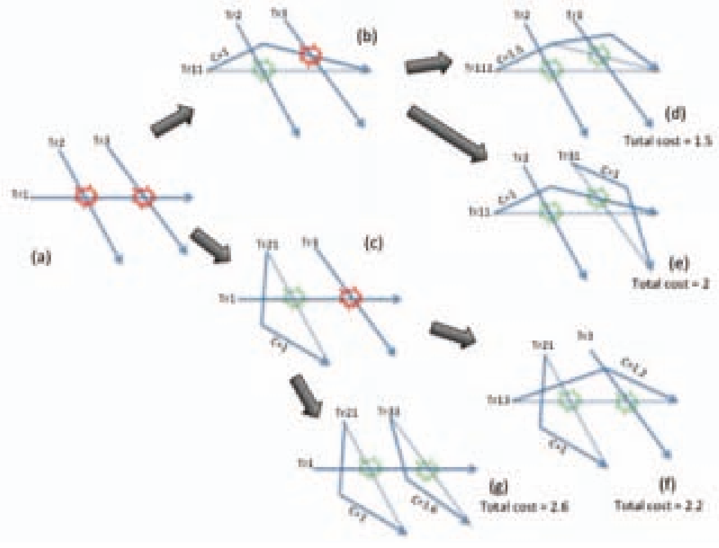


Figure 10: Scenario 3: Effects of solving conflict #1 first

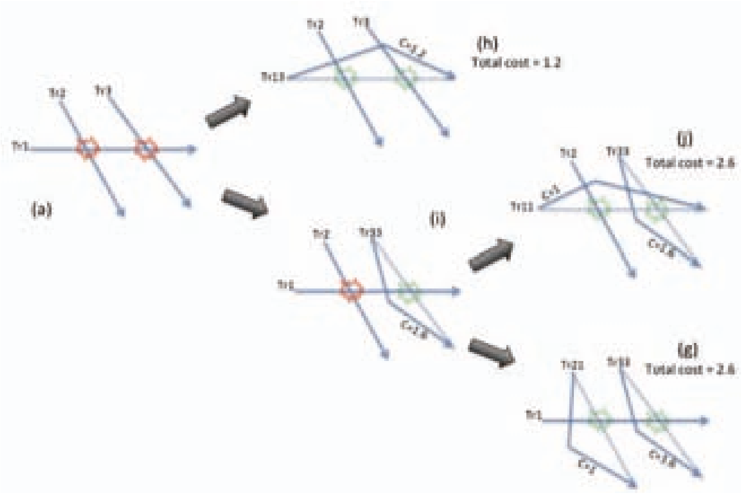


Figure 11: Scenario 3: Effects of solving conflict #2 first

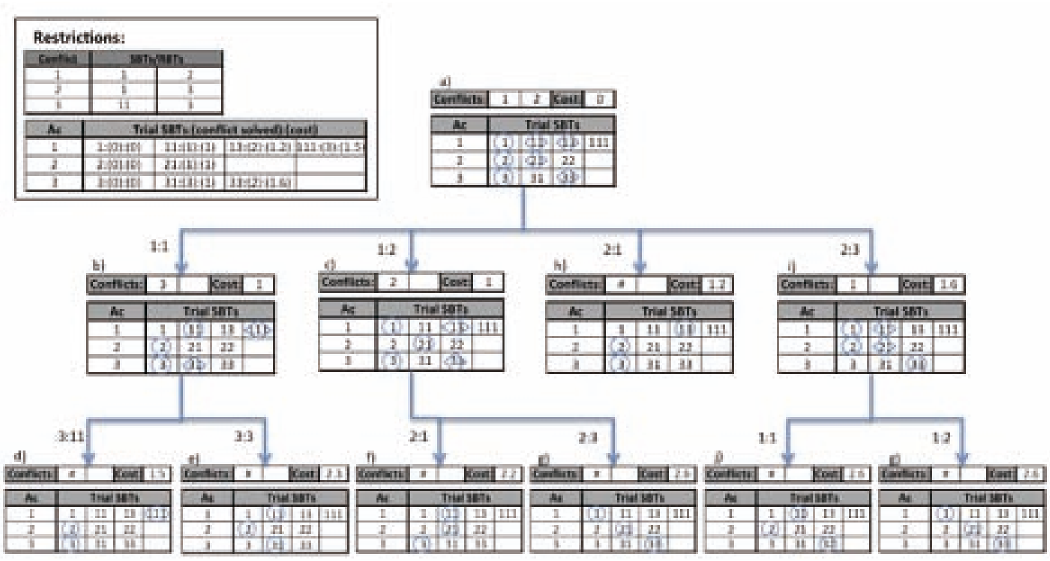


Figure 12: Reachability tree of Scenario #3 presented in Fig. 10 and Fig. 11

The order in which the conflicts are processed during the causal analysis should not affect the final states found in the reachability tree in any case (i.e., no solution/final state should be missed). However, Fig. 10 and Fig 11 (and also in the reachability tree of Fig. 12) note that if conflict #1 is processed first, the causal analysis leads to four final states (*d, e, f* and *g*), whereas if conflict #2 is processed first, the exploration leads to three final states (*h, j* and *g*) with only one of them repeated (i.e., state *g*). This situation is caused by the emergent dynamics (i.e., the domino effects) inherent to the system.

A negative (i.e., destabilizing) domino effect has been noted previously in Scenarios #1 and #2 in which resolution Tr11 solves conflict #1 but generates a new downstream conflict in the network (conflict #3). If resolution trajectories exist for secondary and/or tertiary conflict resolution (i.e., requiring multiple cyclic CD-RTG-CD iterations), then additional branches are opened in the reachability tree to continue exploration (e.g., states *d* and *e* of Fig. 12). Otherwise the current state is declared a non-feasible final state (e.g., state *b,* if no availability of Tr111 and Tr31).

A positive (i.e., stabilizing) domino effect can be identified in Scenario #3. Note that Tr13, which was generated by the RTG to solve conflict #2, also solves conflict #1 indirectly (i.e., a positive network effect occurs). Thus, if conflict #1 is solved first by applying a maneuver to aircraft #2 (state *c*), then conflict #2 must still be solved by applying a maneuver to aircraft #1 (state *f*) or aircraft #3 (state *g*). However, if conflict #2 is solved before conflict #1 by applying a maneuver to aircraft #1 (state *h*), then conflict #1 is indirectly solved and there is no need to maneuver any other aircraft (i.e., *h* is a feasible solution and thus a final state). Additionally, note that due to the presence of positive network effects, certain of the final states may not exactly belong to the Pareto frontier (although they are located nearby). For instance, state *f* is not Pareto-efficient because aircraft #2 can improve its situation by selecting trajectory Tr2 instead of Tr21, thus leading to state *f* (also note that in this particular example, state *f* is not Pareto-efficient, but it might still be preferred to the rest of the scenarios, except scenarios *h* and *d*, due to the total cost).

To ensure the *completeness* (i.e., complete exploration) of the solution space, all conflicts must be processed by opening parallel branches during the causal analysis (point 2 of the causal algorithm presented in Section 4.2: Causal algorithm). This strategy also ensures that, independently of the order in which the branches/conflicts are analyzed, all domino effects (positive and negative) are identified. Taking advantage of the positive domino effects usually leads to more efficient network solutions because fewer aircraft maneuvers are required to solve the same amount of conflicts, i.e., the most-preferred solutions naturally tend to be those with a higher presence of positive domino effects. However, the completeness of the causal algorithm will still ensure the exploration of those states in which the total cost is lower even if additional resolution maneuvers are required. For instance, due to the different costs associated with different types of aircraft, the cumulative cost of maneuvering aircraft #2 and aircraft #3 together (state *g*) could be less expensive than the cost of only maneuvering aircraft #1 (state *h*). One negative effect of considering completeness in the presented causal algorithm is that repeated states may appear, and this is the case for state *g*, which is reached from branches 1:2-2:3 and 2:3-1:2. Selected causal exploration techniques can be applied to avoid symmetries during the generation of the reachability tree.

4.4. Curse of dimensionality

The conflict resolution problem with global optimization is a NP combinatorial problem (Durand, N. et al., 1995) that cannot be solved by exploring the entire state-space. Several strategies have been addressed to address the exponential growth of the state-space problem. First, a causal model with constraint propagation (i.e., activating/deactivating the conflicts and available resolution trajectories) has been described in this paper to reduce the solution space to be explored by modeling the cause-effect relationships and underlying emergent dynamics of the system (see Fig. 13).

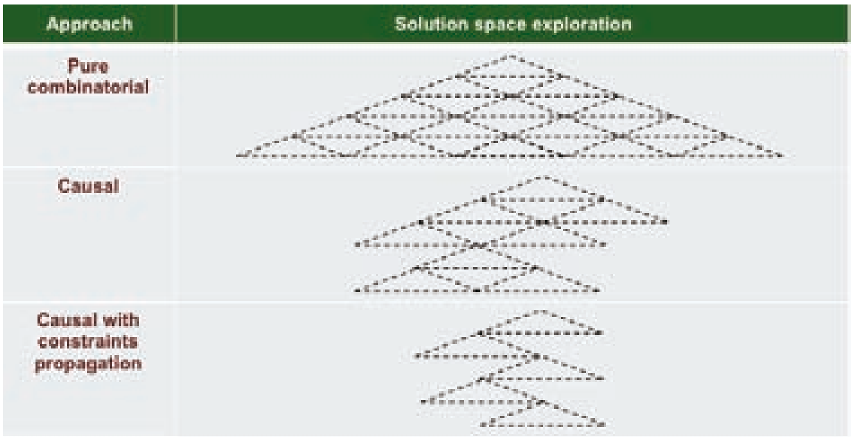


Figure 13: Curse of dimensionality with causal models

However, the size of the problem is still too large and is untreatable even if the amount of trajectories to be processed is increased to only a few dozen. A highly efficient method for avoiding redundancies in the solution space is *clustering*, which reduces the general problem scenario to several sets of independent scenarios (known as clusters) in which each group of trajectories is directly or indirectly connected by conflicts/interactions among them, i.e., if trajectories A and B are in conflict, they are grouped in the same cluster or if trajectory C is in conflict with A but not with B, all three belong to the same cluster (B and C are indirectly connected). Note that the clusters are constructed without consideration of the distance between trajectories, e.g., two trajectories could be located close to each other but not part of the same cluster if they are not in conflict (Nosedal, J. et al., 2012; Durand, N. et al., 1995). Each cluster displays a solution space that is much reduced compared with that of the general problem, and because the clusters represent unconnected/independent sub-problems, they can be processed in parallel. The sum of all independent cluster solution spaces is also considerably smaller than the solution space of the general problem in the absence of any clustering technique, and thus this method also presents important advantages even if the clusters are processed sequentially. Fig. 14 graphically represents this concept.

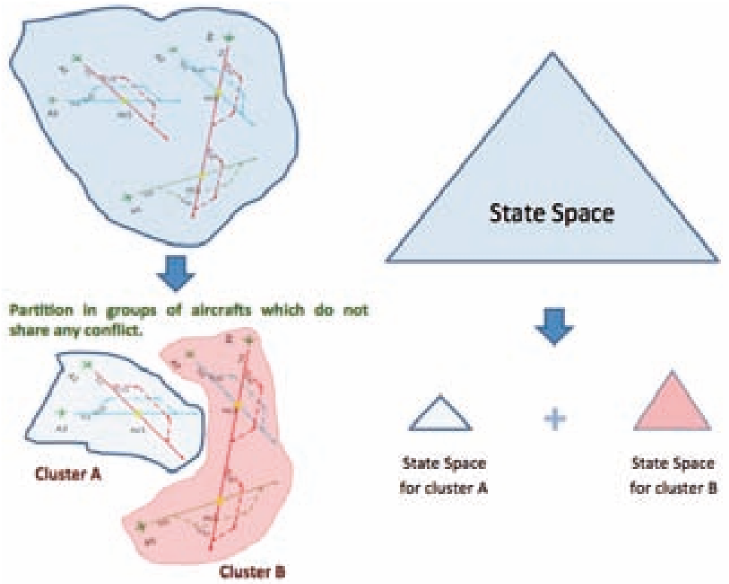


Figure 14: Reduction of solution space via clustering methods

The size of each cluster solution space, even when relatively small, is still sufficiently large to be untreatable for most of the scenarios of interest due to the numerous aircraft interactions. To increase the chances of finding one or several conflict-free scenarios, several resolution trajectories are generated in the RTG. The larger the amount of resolution trajectories per each pair of conflict/aircraft is, the greater the chances of finding feasible solutions in the ICS. However, the local optimality of the resolution trajectories generated by the RTG and the sorting process carried out according to the AU criteria allow the causal algorithm to reduce exploration of the feasible solution space to its Pareto frontier, meaning that only those global solutions closest to the (user-defined) global optimum will be explored (no matter the amount of trajectories generated by the RTG) (See Fig. 15).

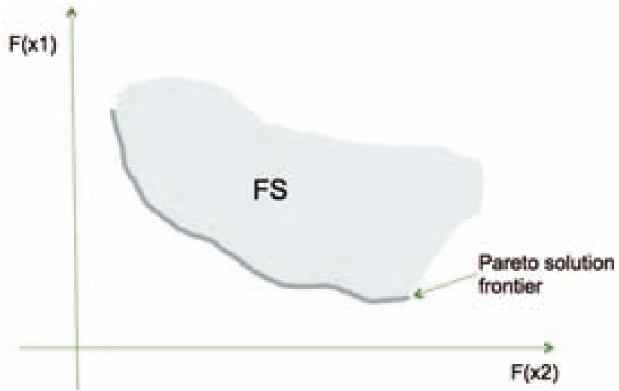


Figure 15: The AU considerations make it possible to reduce the solution space exploration to the Pareto frontier

The above techniques (clustering and exploration of Pareto frontier) reduce the size of the problem to a treatable one, and thus the causal model can provide optimal or near-optimal solutions (due to completeness of the search within the Pareto frontier) for clusters with a relatively small amount of trajectories. However, clusters on the order of a few dozen or more can still present as intractable in practice. Note that at the end of the ICS process, several combinations of conflict-free solutions are delivered. By applying different metrics to measure efficiency, safety, robustness, equity and fairness (among other criteria), it would be possible to determine which of the feasible conflict-free solutions is the most preferred for both the airlines and the NM.

To avoid delivery of an impractical amount of feasible solutions for evaluation purposes, a minimum gradient search can be introduced into the causal model, which requires updating the cumulated cost at each branch step (point 4 of the algorithm presented in Section 4.2: Causal algorithm) and comparing the costs of the states at the same level. By first exploring the branches with minimum cost, the algorithm ensures that the first feasible solution/final state is one with a minimum cost. Thus, the ICS can be restricted to deliver a maximum amount of feasible solutions, e.g., 100 feasible solutions, thus delivering the first 100 feasible solutions that also would represent the 100 conflict-free solutions with minimum cost (according to a certain metric). The metric used for the minimum gradient search might be different than the cumulative cost used in this paper.

5. *SIMULATION AND RESULTS*

To test the CD&CR algorithms and the developed implementation, several simulations were executed using the real air traffic demand data of a yearly peak traffic day (July 1st 2011) provided by EUROCONTROL and simulated with a Trajectory Predictor developed by Boeing Research & Technology Europe to obtain the Direct Routes corresponding to such structured trajectories. Only the en-route segments of the trajectories were considered, i.e., from Top Of Climb to Top Of Descent.

The resulting en-route trajectories were cropped to fit within a spatial region covering most of the European airspace as defined with latitudes in the interval [30, 70], longitudes in the interval [-20, 30] and flight levels from FL130 to FL430. A time-window filter corresponding to two hours of maximum airspace demand during the day (i.e., from 16.00 to 18.00) was also applied to the computed trajectories. The resulting scenario included 4010 trajectories with an average length of 32.5 minutes.

Fig. 16 shows a snapshot of the retained trajectories after the first CD processing, which resulted in a total of 326 conflicts detected among the original trajectories. The conflict regions are represented in red. The RTG process generated 1307 new trajectories, with each one solving at least one original conflict. Only heading change maneuvers (both left and right) were considered for each aircraft in conflict, and trajectories covering more than 50% of the original track distance were heuristically discarded and assumed as unacceptable because of the cost or fuel capacity. Once generated, the trajectories were subsequently processed by the CD module, which detected a total of 2360 new interactions (i.e., secondary and tertiary conflicts). Fig. 17 illustrates the *best* solution found according to the *minimum total delay* metric in this case.

A total number of 284 trajectories were modified to solve all of the 325 conflicts originally detected. The resolution trajectories are represented in green. This difference in the amount of trajectories is a consequence of the ICS algorithm, which *naturally tends* to prioritize those scenarios that gain the most advantage from the positive/stabilizing domino effects.

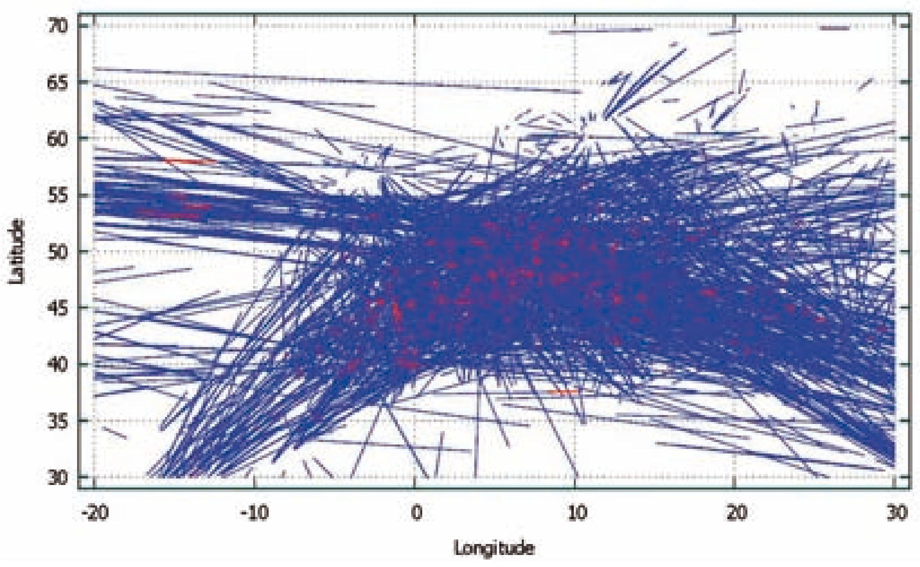


Figure 16: European airspace with 4010 trajectories following Direct Routes; 325 conflicts detected

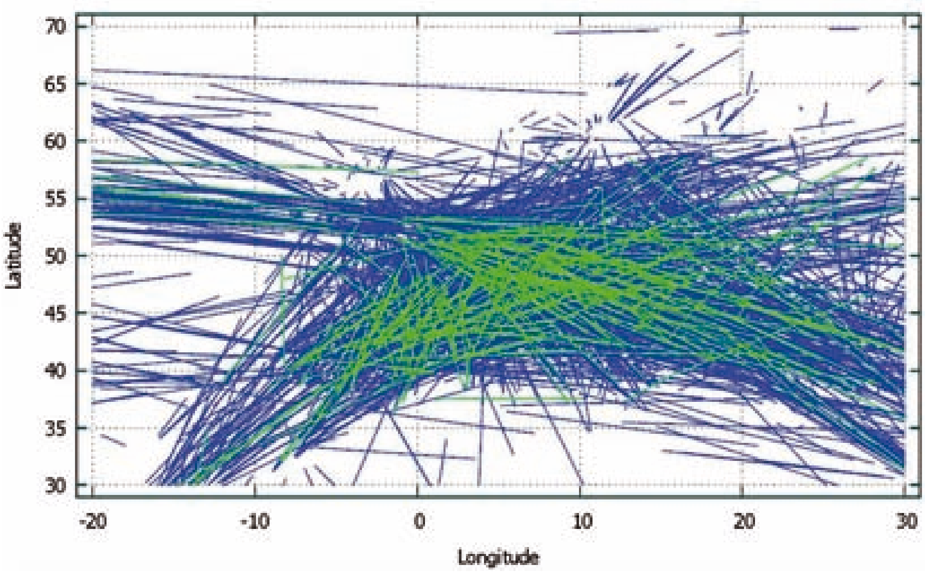


Figure 17: European airspace with 4010 conflict-free trajectories; 3725 original Direct Routes, 284 modified routes, 0 conflicts

Fig. 17 shows the distribution of the identified clusters. Note that the 325 conflicts were distributed among 196 clusters and that 97% of the clusters did not involve more than seven aircraft. For clusters of sizes less than or equal to seven aircraft, the ICS can provide several solutions (if any exist) sorted by a certain metric in less than 1 second, whereas solutions for clusters with sizes of eight or nine aircraft can take up to 2 minutes (simulations for 15, 21 and 22 aircraft clusters were halted after two hours because such processing time was considered not valid for real-time purposes during the experiment even if a CPU that was 10 times faster were considered). For run-time efficiency purposes, those clusters with more than seven aircraft (which represent nearly 3% of the clusters) were re-clustered and reduced to several sub-clusters with a maximum size of seven aircraft. Such re-clusterization was possible after the identification of 11 tightly coupled trajectories with many interactions that contributed to form those clusters with more than seven aircraft (i.e., the 3% of clusters). Altitude transitions were applied to those 11 aircraft (which represent 0.3% of the total traffic scenario) in the regions in which they previously encountered a conflict with another trajectory. In this manner, the existing six large clusters were decomposed into 15 sub-clusters with a maximum size of seven aircraft, thus resulting in a total of 205 clusters in the scenario. Thus the ICS was able to successfully provide (near-optimal) conflict-free solutions for each cluster.

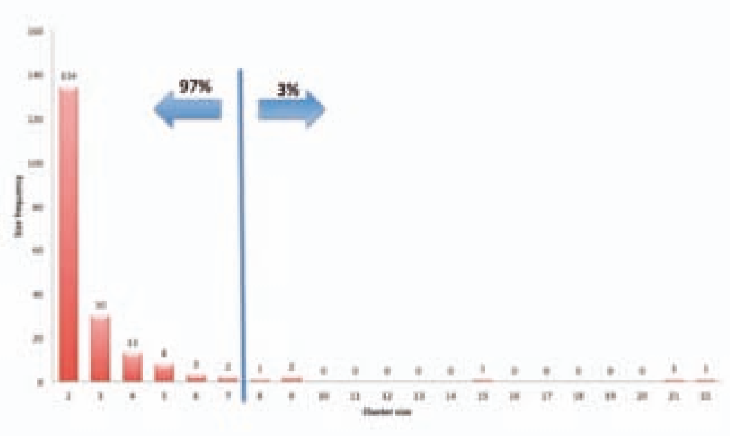


Figure 17: Cluster size distribution

The simulations were run with a 2.6-GHz 64-bit CPU with a processor speed of approximately 650 MIPS and equipped with 64 GB of RAM. The CD&R algorithms introduced in this paper took less than 90 seconds to obtain not one but several global solutions (solutions were limited to a maximum of 10 per cluster, which might lead to a total of 10^{206} different conflict-free network solutions).

Table 1 shows the contribution of each module to the total runtime of the application.

Module	Runtime
CD	8 sec.
RTG+CD	57 sec.
Clustering	10 sec.
ICS	24 sec.
Total	**89 sec.**

Table 1: CDR Simulation runtime

Several simulations have been performed under the STREAM project to test the CD&R algorithms using different scenarios (structured routes, geodesic routes, loxodromic routes and introducing takeoff uncertainties and navigational inaccuracies). The results indicate that the statistical frequency distribution of clusters shown in Fig. 17 is similar in all scenarios with comparable air traffic densities. The computational results (Table 1) were also found to be similar for all considered scenarios (EUROCONTROL, 2012c, 2013; Ruiz et al., 2013; Nosedal, J. et al., 2012; Durand, N. et al., 1995). This observation suggests that the results presented in this paper might be extrapolated to similar European air traffic scenarios in general.

6. LIMITATIONS

The following limitations characterize the simulations presented in the previous chapter:

Only one iteration of CD-RTG-CD cycle has been tested, and thus, no resolution trajectories are provided for secondary and tertiary conflicts. The system could be extended to close a CD-RTG-CD-ICS-RTG-CD cycle to provide resolution trajectories for secondary/tertiary conflicts as soon as a non-feasible final state is identified (limited to a certain amount of searches to avoid potential infinite loops), thus increasing the chances of finding solutions while reducing the amount of information generated.

A limited number of different types of maneuvers have been implemented to solve conflicts, i.e., only heading changes (flight-level changes were not applied as a general method for all conflicts). Introducing flight-level changes, speed changes, combinations of level and speed changes, cooperative resolutions or time constraints (single or multiple) may increase the completeness, optimality and flexibility of the system.

Large clusters (of eight or more aircraft) were re-clustered by applying flight-level transitions to the most tightly coupled trajectories. New strategies in the ICS may be explored to improve the opening of the state-space tree and thus increase the size of the clusters to be solved without re-clustering.

Current resolution maneuvers start and end at the beginning and the end of the route. Other coordinates and times for starting and ending resolutions may be explored to increase completeness, optimality and flexibility of the system.

The absence of uncertainty was considered. Different sources of uncertainty should be introduced in the simulation experiments to stress the system and evaluate the response (e.g., introducing delays in the trajectories or the presence of convective weather).

7. CONCLUSIONS AND FUTURE WORK

A strategic network and collaborative conflict resolution method based on causal modeling has been presented as a fundamental component of the CD&R system architecture used in the STREAM project.

The goal of the Interaction Causal Solver based on a causal model is to explore the emergent dynamics (i.e., domino-effect interactions) between the resolution trial trajectories that are generated to optimally solve conflicts at the local level and with the rest of the trajectories in the network. This model has been designed with the intent to:

a) Reduce the size of the solution space in which to explore and find feasible solutions, i.e., conflict-free route structures.

b) Allow participation of the AUs in several steps of the process and include their criteria in the calculation of the preferred solutions, i.e., facilitating Collaborative Flight Planning through dynamic route allocation.

c) Find global optimal or near-optimal solutions, i.e., the best conflict-free route structures according to the agreed-upon metrics (the model is flexible to different objective functions commonly agreed to by the ATM stakeholders).

d) Find solutions to respond to network and trajectory-level perturbations and dynamically adapt the airspace configuration with a high updating rate for real-time applications.

The algorithms presented in this paper have been scaled and tested with realistic European ATM routes and peak-day flights, and the system has been adapted to consider the curvature of the Earth. Simulation experiments have shown excellent results considering a realistic airspace demand during a peak-day scenario with more than 4000 concurrent Direct Route trajectories. The preliminary results obtained indicate that the proposed model could contribute to developing a subset of the aspects required for Strategic De-confliction during Collaborative Flight Planning in the presence of large number of trajectories, thus representing an evolution towards full ATM automation.

A set of ratios and metrics are currently under development. This information could be useful for making better decisions at the strategic and tactical/operational levels, i.e., choosing the *best* conflict-free scenario among the set of feasible solutions. The introduction of metrics might also enable comparisons among different CR algorithms. Several disturbances (wind, delays, etc.) will be introduced in simulations in future research to test the robustness of the amended trajectories under conditions of trajectory-level uncertainties. This effort will make it possible to establish requirements for the accepted tolerances in the trajectory information at the pre-departure stage as well as to estimate the probability of tactical interventions if certain conflicts appear at the final and tactical levels. Stochastic network perturbations (e.g., convective weather), which affect a large number of trajectories, will also be introduced into the simulations to study the reliability of the system in adapting to network disruptions.

List of Acronyms

ANSP: Air Navigation Service Provider	1
ATCO: Air Traffic Control Officer	4

ATM: Air Traffic Management	1
AUs: Airspace Users	1
CD: Conflict Detection	2
CD&R: Conflict Detection and Resolution	1
CPN: Colored Petri Net	3
CR: Conflict Resolution	2
GOA: Geometric Optimization Approach	7
ICS: Interaction Causal Solver	5
NM: Network Manager	2
NOP: Network Operation Plan	1
NP: Non-Polynomial	3
RBT: Reference Business Trajectory	3
RTG: Resolution Trajectory Generator	5
SBT: Shared Business Trajectory	1
SDS: Spatial Data Structure	5
SESAR: Single European Sky ATM Research	1
SS: State Space	2
STREAM: Strategic Trajectory de-confliction to Enable seamless Aircraft conflict Management	1
TMA: Terminal Maneuvring Area	3
ToC: Top of Climb	4
ToD: Top of Descent	4

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Appendix A

Further Explanations about the CD&R System

A.1 Integration with SWIM

Some of the core ideas of STREAM concept have been presented in the 1st edition of the SESAR Master Class challenge as a proof-of-concept project named Safety SWIM Nets: http://www.sesarju.eu/programme/workpackages/swim/safety-swim-nets-11569.

This integration of STREAM CD&R and SWIM (see Fig. A.1) and the participation in the challenge has been useful to go a step forward in the materialization of the STREAM concepts and also to obtain positive feedback from different EUROCONTROL experts (including CFMU workers and engineers) that has been used to consolidate and improve the proposed ideas.

The application that has been presented is a simplified version of the STREAM CD&R system (still under development at the moment of the challenge). The tool consists on a front-end programmed in C# which enables an interactive GUI for the human user and which en-suits the processes of communication with SWIM through SOAP protocols. See Fig. A.2.

The CD&R corpus of the system has been programmed in C++ to obtain the maximum computer efficiency in the deployment of the algorithms. Communication between the front-end and the CD&R core is done through DLL integration.

As a proof-of-concept version of STREAM only the following SWIM information has been used:

Aerodrome: loaded at local level from the baseline files

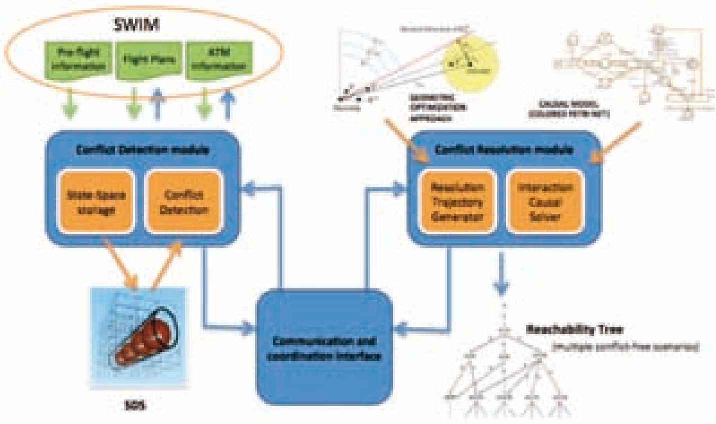


Figure A.1: STREAM CD&R architecture integrated with SWIM

Figure A.2: Safety SWIM Nets application presented in the First SWIM Master Class

Flight list: for the chosen aerodromes and for a given date/time-window.

Flight information request: for each of the flights received a new request is performed in order to obtain some data to reproduce a trajectory from the ICAO Route (specifically the cruise speed and flight level is taken; origin and destination is taken from the Flight List).

For an improved and more complete version of the CD&R system more services would be desirable (still not available in SWIM at the moment of the project), for instance:

- Weather information
- Airports status information
- Updated no-go military airspace zones
- Updated information about congestion and complexity of the network
- Updated information about delays
- Updated information about perturbations that cause deviations from the RBTs
- Other

A.2 Trajectory Identification Through Modular Arithmetic

One of the main features of the CD&R proposed for STREAM is that it considers several alternate trajectories for the resolution of a same conflict. All the resolution manoeuvres computed by the CR for a given conflict are later processed by the CD and thus stored in the SDS. This allows a post-process performed by the ICS causal model algorithm that explores and finds different combinations of trajectories that can be assigned to the different flights of the network and lead to different conflict-free scenarios. Therefore, note that in the SDS a same aircraft/flight may have several alternate trajectories, i.e., trajectories that were generated by the CR to solve same conflicts with different strategies and different manoeuvres (in this preliminary version of the CD&R only HAC manoeuvres have been considered).

Among all the communication interfaces implemented to communicate and synchronize the CD and CR modules, it is of interest to illustrate how the different trajectories are identified. First, note that a same aircraft/flight may have different trial trajectories associated, but only one will be finally approved for being flown. Thus it is necessary to avoid the detection of conflicts among the alternate trajectories that belong to the same aircraft. On the other hand, since each original trajectory of the flights can be involved in more than one conflict, and in turn different alternate resolution trajectories may be generate to solve each conflict, it is necessary to distinguish among the trajectories that solve each of the different conflicts (e.g., a flight may originally have two conflicts, and thus different alternate trajectories may be generated for that flight, some of the solving only the first conflict and some of them solving only the second).

Therefore, the Manager and the CR modules require a method for the univocal identification of the alternate trajectories associated to the same aircraft/flight A in order to rapidly know which are the different aircraft/flights in conflict with A and also which of their specific alternate trajectories are in conflict.

An efficient way to univocally identify and synthesize the required information has been designed by using Modular Arithmetic. The idea is to generate different trajectory identifiers (idt) using the following formulae:

$$idt = f\left(idt_0,\, l,\, nc\right) = \begin{cases} p = nc\left(L+1\right) + l \\ idt = p\left(N+1\right) + idt_0 \end{cases}$$

, being N and L two constants that respectively refer to the number of aircraft/flights in the considered scenario, and the maximum number of alternate

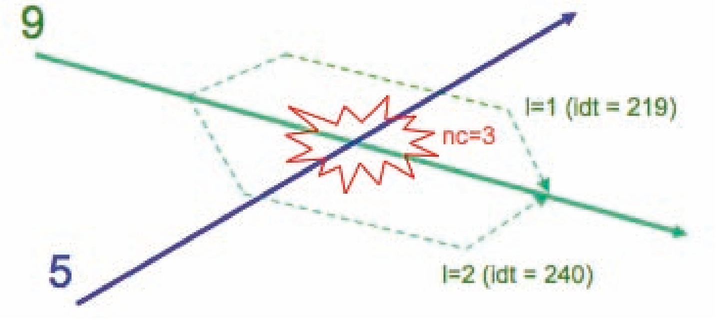


Figure A.3: Example of a conflicted scenario to show the trajectory identification algorithm

trajectories that the CR can propose (it is parameterizable) to solve a single conflict. The input of the function is formed by the *aircraft/flight identifier* $(0 < idt_0 \leq N)$, the resolution *manoeuvre identifier* $(0 \leq l \leq L)$, and the *conflict identifier* nc $(0 \leq nc)$,.

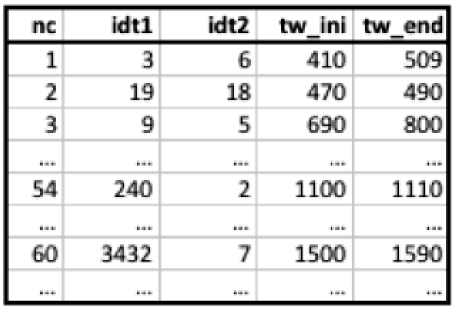
As an example, consider $N = 20$ and $L = 3$. In the following Fig. A.3 the aircraft with $idt_0 = 9$ is in conflict with aircraft $idt_0 = 5$. Consider that only two manoeuvres are proposed by CR to solve the conflict $nc = 3$. One of the resolution maneouvers is a left-turn (identified with $l = 1$) that generates a new trajectory identified with $idt = 219$, and the other is a right-turn (identified with $l = 2$) that generates a new trajectory identified with $idt = 240$).

With the use of modular arithmetic to generate the trajectory identifiers, it is possible for the CD to process the new trajectories #219 and #240 with no detection of conflicts between the trajectories that belong to the same aircraft/flight. To know if two aircraft, idt1 and idt2, belong to the same aircraft the CD has only to check the following condition:

$$idt1\, mod\, (N + 1) = idt2\, mod(N + 1)$$

This way of generating idt's is also useful for the Manager and CR modules to have an efficient resolution manoeuvre record for those trajectories that have been evolved to solve several detected conflicts. For example, consider the following list of conflicts in which a certain trajectory with $idt = 3432$ can be found in the 60th row:

With the computation of $idt/\,(N + 1)$ and $idt\, mod\, (N + 1)$ it is possible to obtain p and idt_0 respectively, and by computing $p/\,(L + 1)$ and $p\, mod\, (L + 1)$ it



nc	idt1	idt2	tw_ini	tw_end
1	3	6	410	509
2	19	18	470	490
3	9	5	690	800
...	...	...	...	...
54	240	2	1100	1110
...	...	...	...	...
60	3432	7	1500	1590
...	...	...	...	...

Figure A.4: Conflict table information of an example scenario

Figure A.5: Modular Arithmetic application to obtain the historical record of a trajectory

is possible to obtain nc and l respectively. In this case (Fig. A.5), $nc \neq 0$, which means that another previous resolution manoeuvre was previously applied to the original trajectory of the flight $idt_0 = 9$. Thus, with the conflict number $nc = 54$ and from the conflict list, it is possible to find the idt of the previous trajectory (id_father), and since $N < 240$ it can be rapidly known that this trajectory was also generated by the CR to solve another previously found conflict. Following the same procedure (i.e., $240\, mod\, (N+1) = 9$ and $p/\,(N+1) = 3$), the original trajectory idt can found in the third row of the list of conflicts ($nc = 3$).

Note this method allows a backtrack historical trajectory record in which the only piece of data necessary is the the trajectory identifier, e.g., with $idt = 3432$ it can be known that the aircraft #9 had a conflict with aircraft #5, whose conflict could be solved by turning-right ($l = 2$), and that that the new trajectory ($idt = 240$) has found a downstream conflict with aircraft #2 ($nc = 54$), whose conflict could in turn be solved by turning left ($l = 1$).

Finally, the backtrack manoeuvre record of the trajectories could also benefit the CR. For example, to solve the conflict $nc = 60$ between $idt = 3432$ and $idt = 7$, the CR could take into consideration the past manoeuvres to determine which manoeuvre would be better for the resolution of the conflict.

A.3 Adaptation of the SDS to Consider the Curvature of the Earth

The results given in Article 2 and Article 5 have been used the concept of Geodesic SDS since the simulated scenarios have required to consider the curvature of the Earth due to the large dimensions of the European airspace. Note that the concept of Geodesic SDS has not been sent to journals for publication, thus no information is given in the Articles presented in Chapter 7 of this dissertation.

The most important change to generate a Geodesic SDS with respect the regular SDS (i.e., planar) is to translate from meter units to degree units, which in turn introduces a little handicap: the corresponding conversion between metres and longitudinal degrees has a variable value depending on the latitude of the Earth (i.e., the equivalence of 1 degree in metres is lower at higher altitudes).

For simplification purposes, the discretization of the SDS implemented in the CD&R system has been set to fixed degree-unit steps (variable discretization could be also possible): 0.2 degrees bin-size in the latitude dimension (which corresponds to 12NM approx.) and 0.5 degrees in the longitude dimension (which corresponds to a size between 10NM and 26NM in the considered European airspace depending on the latitude, i.e. from latitude 30º to 70º).

Note that the application of a fixed longitudinal step causes that, in the latitudes close to 30º, the longitudinal size of the bins is more than two times bigger the optimal size that would be required to minimize the amount of pairwise comparisons (i.e., 26NM instead of the optimal 10NM size). However, since the SDS acts as a filter in 4 dimensions (space and time), and since the size of the bins is still relatively small compared to the distances covered by the trajectories, the SDS still can perform as a good/powerful pruning filter. Indeed, no relevant performance degradation has been detected with respect to the results obtained with a “planar” SDS.

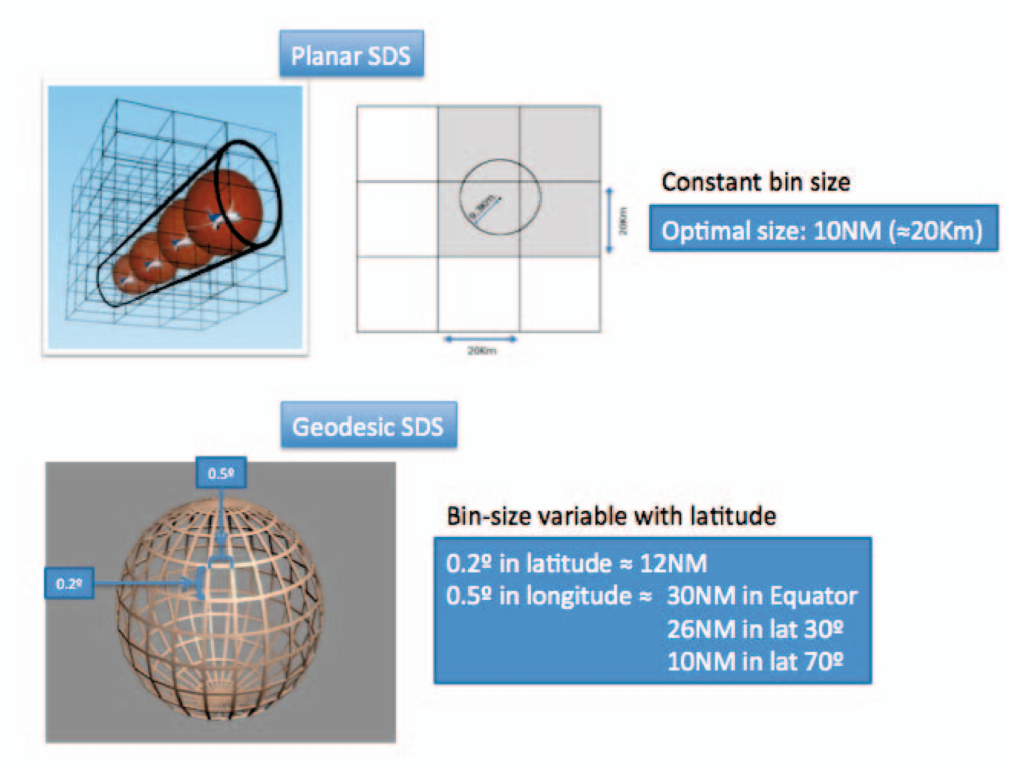


Figure A.6: Evolution of the SDS towards a Geodesic SDS

A.4 Adaptation of Geometric Optimization Approach Algorithm to Strategic De-confliction

The advantage of the GOA model is that it takes into account the geometric characteristics of 2 aircraft trajectories in conflict (see Fig. 3.12 on page 85) and are utilized to determine **closed-form analytical expressions** for conflict avoidance commands. However, the usage of GOA concepts for the strategic de-confliction approach proposed by STREAM has required dealing with three major limitations of original GOA algorithms:

1. The geometric relative framework was based on **planar geometry**. Such approach works well for tactical de-confliction purposes, since the distances covered by aircraft during a 20-minute time window are short enough (i.e., less than 1000Km) to allow the consideration of a planar geometry. However, for the strategic purposes considered in STREAM project, the curvature of the Earth must be considered and thus the GOA algorithms must be updated.

2. Trajectories are assumed to be **straight lines** (i.e., fixed course lines). Again, such approximation is precise enough if tactical amendments are under consideration (i.e., relatively short distances). However, for strategic route allocation the curvature of the Earth must be taken into account since distances are often relatively large. The shortest distance between two points in a spherical shape is represented by a geodesic curve (the equivalent of a straight line in planar geometry). The problem with geodesic trajectories is that they require constant course changes, which are difficult to be flown by human pilots. However, current FMSs and aircraft autopilots are able to fly geodesic trajectories (also called orthodromic trajectories) with precision, and thus the GOA algorithm had to be updated for the consideration of geodesic Direct Routes as proposed in the STREAM concept.

3. **Fully synchronous** co-existing trajectories are assumed. Again, this assumption works fine for tactical purposes, since conflicts are detected between aircraft that are already airborne at the moment of the CD process and thus at the moment of applying a resolution amendment. However, for strategic purposes, in which the resolution amendments are applied from the departure (or the TOC) of the trajectory, it must be considered that the trajectories involved in a conflict may start at different absolute times. This requires updating the GOA algorithms to take into account the computation of the relative geometric framework between the asynchronous amendment starting points of the two trajectories.

In order to manage with the above three GOA limitations, the following updates have been done:

1. The original GOA mathematical formulae have been adapted to **consider the curvature of the Earth**. Based on Mercator conformal transformation, the (non-developable) Earth sphere (Fig. A.7.1) is divided into several planar projections or time-zones (Fig. A.7.2) that can be put together in the same plane with discontinuities (i.e., gaps) among them (Fig. A.7.3). To fill those gaps and obtain a uniform planar surface, while having a conformal projection (i.e., the true course between every pair of points is maintained), each of the parallels on the map are stretched horizontally (i.e., in east and west direction) by a factor q, which depends on the latitude of that parallel (Fig. A.7.4). This stretching factor can be expressed as $q = lat/ln[tg(lat/2 + pi/4)]$, and thus each longitude can be repositioned in the new planar surface as $long\text{'} = long/q$ [63, 3]. The computation of the relative bearings, the relative velocities and the resolution courses has been updated taking into account the required transformations for the effective use of GOA in a spherical geometry. The true course of the trajectories has been used instead of the straight slope that was used during the usage of UTM projections in STREAM D4.1 [37, 45].

2. Since **geodesic trajectories** (with constant variation of the true course) has been introduced in the STREAM concept, and since the GOA algorithm cannot be easily updated to take into account variable relative courses between trajectories, the following approximation has been used (see Fig. A.8): 1) the first loss of separation is identified (both in space and time) between the two original geodesic/orthodromic trajectories in conflict, 2) a loxodromic (i.e., constant true course line) approximation of the trajectory is considered between the starting point and the *first loss of separation*, 3) a resolution 4D waypoint is computed by using the previous loxodromic approximation in the GOA algorithms, including an extra buffer to the required safety separation and adapting the average speeds to synchronize the geodesic and loxodromic tracks (in order to minimize the errors of those approximations), and finally, 4) the new resolution trajectory is computed as one geodesic line from the origin up to the resolution point, and another geodesic line is computed from the resolution point up to the destination of the flight.

3. In order to obtain alternate resolution trajectories with the GOA algorithm, both trajectories in conflict must be referenced to a relative geometric framework, which implies that they coexist at least during the time window in which the resolution manoeuvre is executed. To adapt the GOA algorithm to strategic purposes (i.e., conflict-free route allocation), it often requires

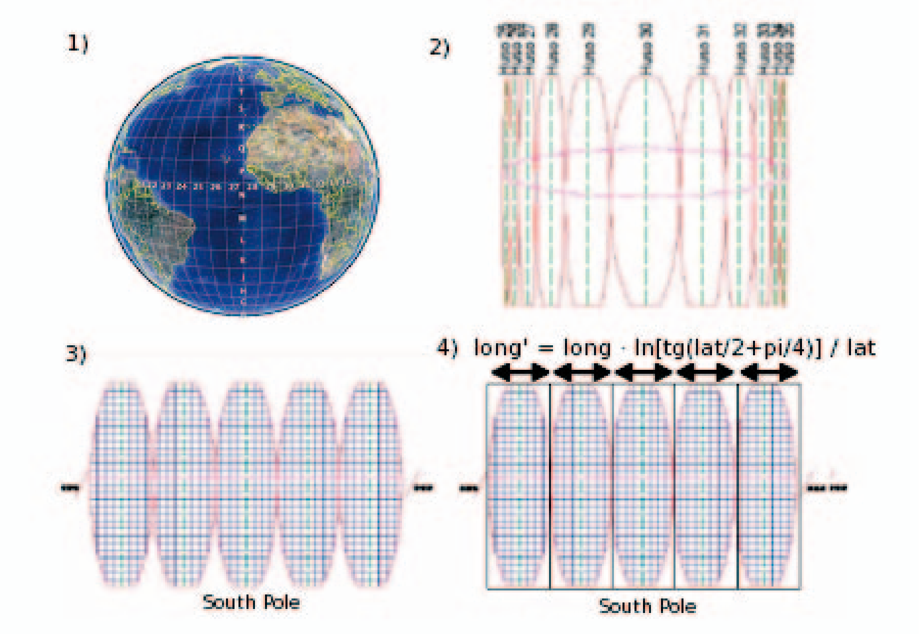


Figure A.7: Transformation from the curved Earth to a planar geometric framework

the **artificial synchronization** of the trajectories in conflict, thus needing to calculate a *false origin* for each pair of trajectories in conflict (except in the rare cases in which both trajectories start at the same time). For instance, see Fig. A.9 in which trajectory A starts at t0 and trajectory B at t0+100. To compute the resolution commands for trajectory A, it is necessary to make a time projection of trajectory B as if it had started at t0 (thus considering a *false track* for trajectory B), whereas the computation of resolution amendment commands for trajectory B requires a false origin to be applied to trajectory A, as if it had started at time t0+100.

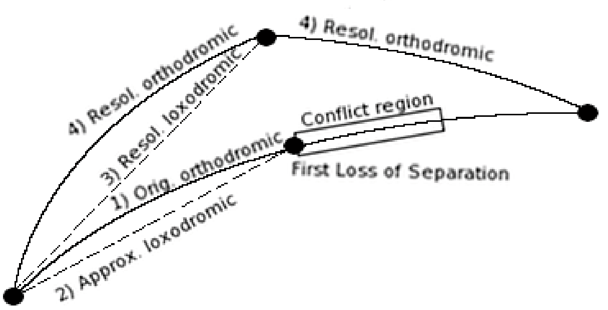


Figure A.8: Adaptation of the GOA algorithms to adapt to the presence of geodesic trajectories

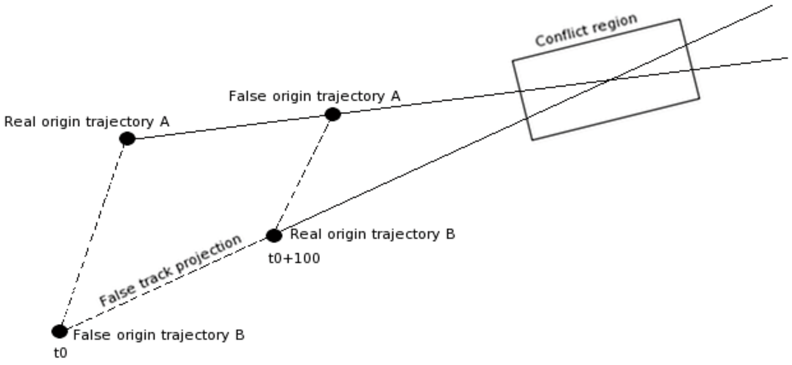


Figure A.9: Adaptation of the GOA algorithms to adapt to the presence of desynchronized trajectories

A.5 Strategies to Tackle some Sources of ATM Uncertainty

For the purposes of this dissertation only a simplified categorization of uncertainties has been considered (see the ConOps in Chapter 3.2). However, during the design process of the CD&R nominal models presented, a more realistic version of those algorithms has been also taken into account, thus actually allowing the introduction into the models of different sources of uncertainty and non-deterministic behaviour that may affect to both the strategic and tactical ATC/ATM operations.

Uncertainty and non-determinism are different concepts. *Uncertainty* is defined as the condition of being partially unknown or in doubt. *Non-determinism* in a system implies that the future states of the system cannot be predicted even if its present and past states and inputs are perfectly known. Note that in the presence of uncertainty the system itself can be deterministic, but its current or future states may not still be perfectly known. Using the theory of stochastic processes it is usually possible to obtain the future states of a deterministic system that is affected by uncertainty, not in a purely deterministic sense, but rather in a probabilistic sense (for instance, as the distribution of a random variable).

Recently, five categories of uncertainty that affect the ATM have been under discussion by the scientific community [1]:

- Airborne Trajectory uncertainty (i.e., uncertain execution of the planned trajectories)
- Flight uncertainty (i.e., includes the trajectory execution uncertainties but extends to other phases prior and after the flight execution phase e.g., departure delays)
- Traffic uncertainty (i.e., uncertainties affecting flows and airspace sectors)
- Network uncertainty (i.e., strong disturbances, such as adverse weather)
- Weather uncertainty (i.e., the weather is interpreted as a system that behaves independent of, but affects to, the ATM system).

In this dissertation, a complementary categorization of the uncertainty has been considered according to its impact in the CD/CR research proposed:

Parametric uncertainty: the model representing the ATM system is known but some parameters are somehow imprecise. Following examples may impede a fully precise aircraft navigation control:

- Weather / wind: sudden wind gusts, wind prediction errors, temperature gradient...
- Aircraft performance: aircraft current mass, flight execution...
- Pilot execution: time of response, maneuver execution imprecisions...
- Aircraft instrumental imprecisions: altimeter, CAS/IAS,...

Perturbations: unexpected events external to the model that requires a control action to drive the ATM system to the desired state

- Deviations: aircraft flying outside the expected nominal trajectory, considering certain spatio-temporal tolerance interval. Some deviation can be caused by human error.
- Delays: temporal deviation produced before takeoff. Note that since this class of uncertainty could be structured (i.e., structured uncertainty), delays may become parametric uncertainty in some cases.
- Weather / wind: in certain unstable atmospheres, like storms or high-turbulent areas, the prediction of the weather is degradated and can affect the capacity of the air sector, thus affecting a large number of flights and requiring a network reconfiguration.
- Contingencies: Natural (e.g., volcano ash), human events (e.g., wars) or any other kind of contingency can force to readapt the ATM network.

Noise: Measuring errors of the current ATM system state (e.g., the aircraft could be in the desired positions but the ATC observe a false deviation from the nominal trajectory due to radar tracking errors).

- Positioning/tracking errors: Radar, GPS, etc. are technologies that are not exent of uncertainties, which should be introduced in the ATM model.

Note that the classification of the particular items inside the three categories (i.e., parametric uncertainty, perturbations and noise) may be variable, depending on:

- The particular model/system under analysis (e.g., delays can be considered a perturbation or parametric uncertainty, according to different ATM models and objectives).
- The current know-how of the system (e.g., advances in the meteorological understanding can provide with the ability of forecasting the weather with more precision, thus indirectly contributing to refine the control of flights and thus improving the predictability of the ATM).

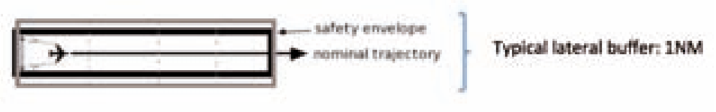


Figure A.10: Application of spatial buffers to tackle some sources of uncertainties

- The available technology (e.g., new weather sensors can provide with better weather predictions).
- Others.

In this research it is accepted that the trajectory predicted/simulated by the airborne systems will be always different (and more precise) than the trajectory predicted/simulated by the ground systems. However, the CNS technologies that are assumed for SESAR shall allow a 4D predicted trajectory to be calculated airborne and transmitted to the ground ATM stations. These modern CNS technologies shall also allow the precise adherence of the flown trajectory to the predicted/planned trajectory (within reduced and accepted navigational tolerances), and the precise flight monitoring in real-time. Therefore, it is expected that a further research future work on the following three strategies shall contribute (together with the excellent computational performance obtained in the CD&R system) to the actual en-route synchronization of traffic in the presence of several sources of ATM uncertanties:

1. **Spatial buffer**
   Due to the imprecisions of the navigation and flight control systems some (relatively little) deviations of the trajectory actually flown can be observed with respect the expected/planned/predicted nominal trajectory. Over the years, this kind of uncertainties in flight execution has been tackled by introducing extra safety buffers to the minimum distance separation (see Fig. A.10). Nowadays, with the improvement of the navigation and control technologies it is possible to fit any of these deviations within a bounded region defined by 1NM per each side in the horizontal plane [41]. The noise (i.e., tracking errors) derived from the current surveillance technologies can be also ignored within the proposed buffer range [56].

   Note that in the nominal scenarios of this research the distance applied in the CD process to determine the presence of conflicts has been parameterized to 5NM, i.e. the current ATM separation standard. Note that it can be assumed that this safety standard distance (i.e., the 5NM) has been defined by ICAO experts taking into consideration the related navigation uncertainties of flights, meaning that the application of extra buffers could be in some cases not necessary at all. In

Figure A.11: Structured uncertainty of delays

any case, the application of an extra buffer is a parameter for the CD&R system that can be easily modified according to any parametric study that may suggest the use of any other separation distance rather than the nominal 5NM (see for instance the Section 5.5, that shows experiments with uncertain scenarios).

2. Temporal buffer

Perturbations in the Expected Time of Departure (ETD), i.e. *delays*, is one of the main concerns of SESAR, since delays have strong traffic de-synchronization effects and thus also have a direct impact in the ATM capacity. Fortunately, delays are a kind of uncertainty that can be modelled through statistical distributions (thus also called *structured uncertainty*). See Fig. A.11. This opens the door to the application of temporal buffers to the trajectories in order to mitigate with a certain probability (i.e., in a certain number of trajectories) the de-synchronization effects of delays.

Under this research the concept of temporal (or longitudinal) looseness has been developed (see Article 3) as a way to understand and control the de-synchronization network effects caused by delays. After properly configuring and analysing the content of the SDS, which contains all the nominal planned trajectories, it is possible to obtain the information about the *temporal/longitudinal looseness*, λ, for each of the trajectories, i.e., how much time a trajectory can be advanced or delayed without entering in conflict with another trajectory (whilst preserving the speed profile defined in the flight plan).

Figure A.12 illustrates the concept of temporal looseness: for a given trajectory (SBT or RBT), it is possible to find how many units of time it can be advanced or delayed without causing interactions (i.e., conflicts) in the network. In the example of the figure the *current SBT/RBT* could be advanced 3 units of time or delayed 5 units of time without causing any conflict in the network.

Formally, the temporal looseness λ can be defined as the time-window formed

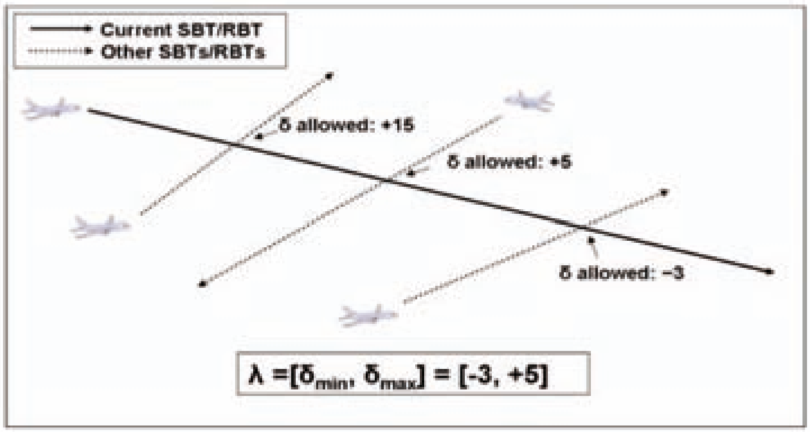


Figure A.12: Temporal looseness of a trajectory

by the minimum and maximum *delays*, δ_{min} and δ_{max} , that a given trajectory can afford while still being conflict-free, having the rest of the trajectories static:

$$\lambda = [\delta_{min}, \delta_{max}]$$

Note that δ_{min} could be negative, i.e. $\delta_{min} < 0$, if the trajectory can be advanced in time, and δ_{max} could also be negative, $\delta_{max} < 0$ if the only way to solve the conflicts is by anticipating the flight. In addition, both δ_{min} and δ_{max} are bounded by technical and service restrictions, such as the maximum increment of speed allowed for a given aircraft and the maximum deviation allowed from the user-defined Estimated Time of Departure (ETD) and Estimated Time of Arrival (ETA).

The calculation of λ can help to identify trajectories that are more sensitive to delays (i.e., less robust) and give this relevant network information to the airport controllers in order to prioritize the departures according to such information. A post-processing of the conflict-free trajectories stored in the SDS and their temporal looseness would also allow a sensitivity analysis regarding the influence of departure delays (i.e., on the ETD) of the RBT on the number of conflicts/interactions and on the complexity of their solution. The sensitivity analysis could provide highly valuable information on the airport departure schedule (DMAN), in trying to preserve the ETD of those flights that could generate extra workload to controllers.

Thus, it is possible to compute the following data for each trajectory from the

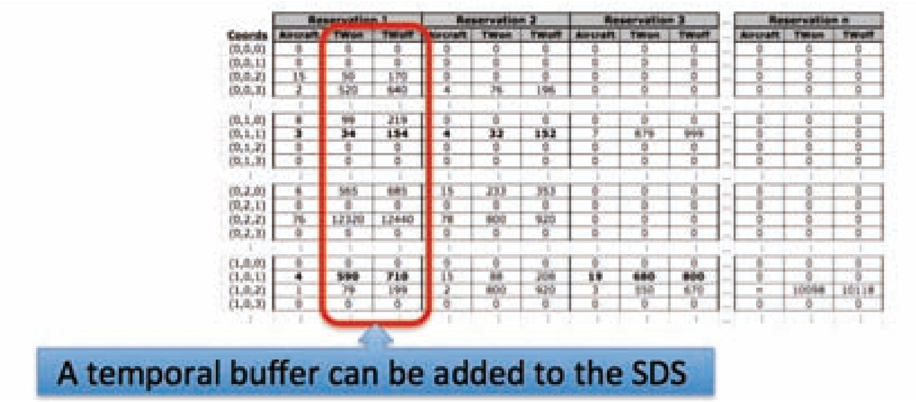


Figure A.13: Application of temporal buffers to tackle some sources of uncertainty

different rows of a SDS properly configured:

- The maximum departure delay δ_{max} (or advance δ_{min}) that could be accepted without generating a new conflict with other trajectories. This information can be obtained by computing the minimum time distance between two adjacent reservations (columns). Information about the trajectories involved in each potential conflict is also provided.

- The number of conflicts given a certain delay out of the range of the trajectory longitudinal looseness, $\delta \notin \lambda$. This data should be provided together with some indicator describing the concentration or distribution in time of these potential conflicts. It is easy to see that knowing that an ETD delay could generate 25 potential conflicts is valuable information, however it lacks of a complexity measure related to the resolution. The same information with a measure indicating that the 25 conflicts are concentrated in the same area, or are distributed along the trajectory, provides better knowledge about the impact of the delay on the ATC workload.

The concept of *contract tube* proposed by the PHARE project [76] is a good choice to easily represent the resulting constraints and their degree of looseness, meaning, a set of 4D windows located at sensitive points along the trajectory, depending on the airspace configuration and the ATM needs.

A possible way of implementing those concepts in the CD&R nominal algorithms presented in this dissertation is based on the introduction of a *temporal buffer* [76] that can be added as extra information in the SDS (see Fig. A.13). This temporal buffer extent the temporal utilization of a nominal trajectory for the spatial resources used in the nominal flight. Note that this buffer can be parameterized according to the statistical distribution of delays in each airport, thus it is possible to control the level of robustness desired for each trajectory and for the network (there is a trade-off between the ATM capacity loss due to the lack of robustness and the airspace capacity loss due to the application of larger time-space buffers). In this manner, if the applied buffer is lower than the actual temporal looseness, the CD module will detect a conflict (even when the nominal trajectories perhaps are conflict-free). The CR (i.e., the RTG and ICS modules) will find the best network trajectory combination for a desired level of robustness, thus being flexible to different policies to deal with the trade-off between flight efficiency and ATM capacity. Note that the bigger the temporal buffer, the bigger is the spatial separation among nominal trajectories. Thus, the introduction of temporal buffers to mitigate the impact of delays has direct consequences on the airspace capacity.

A parametric study should be performed (it is out of the scope of this thesis) to identify which is the optimal level of robustness to delays, having into account that the maximum robustness (i.e., temporal buffer fitting 99% of delays distribution) may quickly degrade the airspace capacity because of the throughput reduction (i.e., bigger spatio-temporal separation among trajectories causes lower ATM throughput), while the minimum temporal buffer may imply an increment of ATC workload (because of the higher probabilities associated to the occurrence of conflicts during flights execution), thus also lowering the ATM capacity.

On the other hand, the calculation of λ can also help the CR to provide resolutions based on speed regulations. Referring to Fig. A.13, the row of the SDS associated with the coordinate (0,1,1) shows that aircraft 3 and 4 are potentially in conflict, since both aircraft want to use the same coordinate in incompatible time-windows (i.e., [34-154] for aircraft 3 and [32-152] for aircraft 4). Aircraft 7 also wants to use the same coordinate, but now the time window, [879-999], is not in conflict with any aircraft. The longitudinal looseness of aircraft 3 in this coordinate, (0,1,1), in which it can be delayed without entering in conflict with aircraft 7 is given by 789-154 = 725 time units. Assume there is no other coordinate for aircraft 3 with less looseness, so the total looseness of the trajectory for aircraft 3 is the same as calculated in point (0,1,1). It means that aircraft 3 can be delayed 725 seconds without entering in conflict with any other aircraft. So, a possible way to solve the conflict between aircraft 3 and aircraft 4 is by delaying the ETD of aircraft 3 in 152-34 = 118 seconds. Since 118 s. is lower than 725 s., which is the total temporal looseness of aircraft 3, it is ensured that this delay will solve the conflict without creating a new one in the considered airspace.

A set of metrics and methods could be developed to obtain and synthesize the information stored in the SDS in order to perform a sensitivity analysis of the

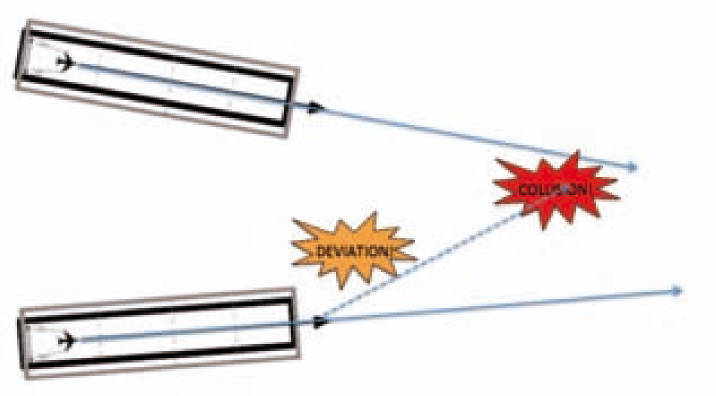


Figure A.14: Risk-of-deviation during the flight execution phase

CR trajectory amendments, taking also into consideration the flight and delay uncertainties and thus the probability of conflicts.

3. Risk-of-deviation probability

In control engineering, a perturbation is a non-controlled event, external to the controller model, which causes a deviation of the system output from the reference consignee, and thus requires a control action in order to drive the system to a new desired stable state. In the ATM system, when a flight does not follow the expected nominal trajectory (i.e., RBT), within a certain spatio-temporal buffer, it is called a *deviation*. In such cases, the ATC usually generates control actions (indirectly, by sending instructions to the pilots, who are expected to execute the control consignees) in order to correct the system deviation and avoid possible conflicts or collisions.

Modern automated CD systems such iFACTS constantly evaluate the probability of collision in a look-ahead time-window of 20 minutes and give this information to tactical controllers so they can be aware of the possible consequences of any potential trajectory deviation. Tactical controllers take action (usually between 6 and 10 minutes before) when the risk associated to a potential collision is considered too high, even when the nominal trajectories may not be in conflict. See Fig. A.14.

Since the CD&R algorithms of this research aim at joining the existing gap between the strategic route allocation of flights and the tactical ATC procedures, it is vital to introduce the point of view of ATC into the strategic planning process. Therefore, the proposed strategic de-confliction nominal algorithms can be extended with a risk-of-deviation model based on probabilistic 4D tubes that can

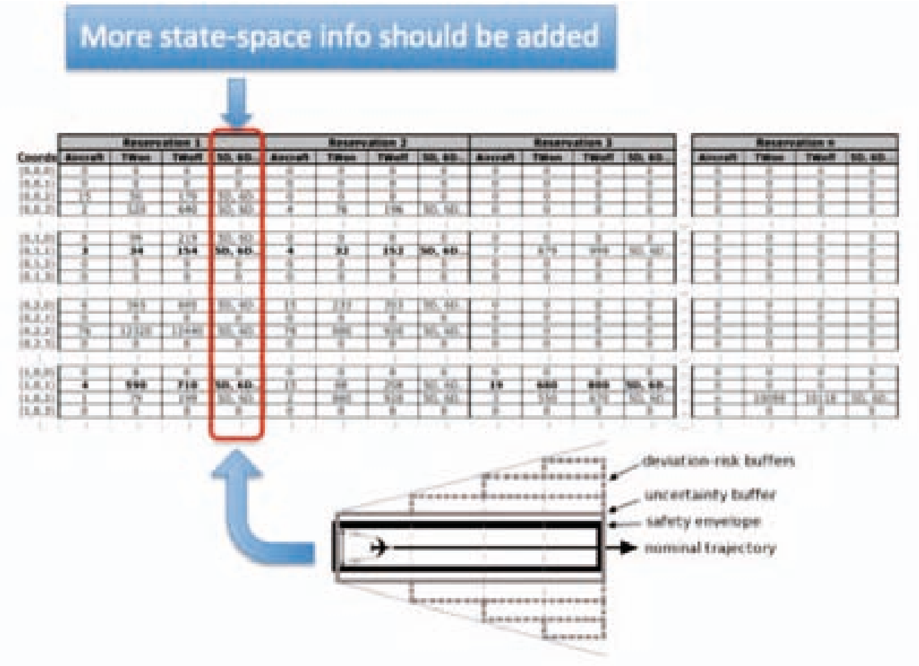


Figure A.15: Application of n-dimensional ATM information to tackle some sources of uncertainty

be computed for every time-instant of the nominal trajectories, and projecting the uncertainty along a certain time-window look-ahead (typically 20 minutes) after which the evolution of uncertainty can be truncated (controllers are expected to take action before that time in case a deviation is detected)[19]. See Fig. A.14.

The parameterization of those probabilistic 4D tubes (i.e., the size and the associated probability values) can be obtained through off-line TP studies and customized for every type of aircraft and weather conditions. The parameters obtained through exhaustive off-line studies can be introduced in a knowledge database optimized for the access of the strategic CD&R algorithms, in a way such that by taking the information of the aircraft model and the weather conditions (among other), the required parameters to build the probabilistic 4D tubes can be efficiently accessed for a real-time execution of the algorithms.

With regards to the technical aspects, the risk-of-deviation model can be adapted to the CD&R algorithms of this research thanks to the flexibility of the SDS to store n-dimensional state-space information. In this case, the reservation of the ATM spatial resources (i.e., little portions of airspace) can be made during the CD process complementing the 4D information with probabilistic information A.15. Thus, at every moment in which a distance comparison is performed between two trajectories, which potentially may share a certain 4D coordinate or space, the CD algorithm should multiply the probability values (i.e., intersection of probabilities) in which those aircraft may cross such airspace region. Given a threshold (considered *safe-enough*), the CD can determine if the risk of collision is too high and thus consider it as a conflict if necessary(thus the CR will provide resolution alternatives).

Figure A.16 shows the same scenario as in Fig. A.14 but with one of the trajectories amended by the CR system because of the introduction of the potential deviation models. Note that in Fig. A.14 the nominal trajectories were not in conflict and thus the CD&R algorithms did not amended any of the trajectories. However, if such a scenario was delivered from the strategic planning layer to the tactical ATC level, two negative effects would occur: first, the ATCOs will increase their workload because they would detect a too-risky situation and thus they should take control actions (i.e., navigation commands requested to pilots), and second, the control actions of the ATC could modify the strategic network plan without considering a global network view, thus causing potential destabilizing network effects and more inefficient flight executions. Fig. A.16 also shows that the price of introducing this uncertain deviation model is to have less efficient trajectories and lower airspace capacity due to sparer trajectory separations. Nevertheless, it is expected that the gains in predictability and robustness, together with the expected reduction of the ATCOs workload, might compensate the cost of considering this uncertainty model.

There is no doubt that many studies on uncertainty factors and their propagation through the airspace system will be refined in the near future. In this sense, it is expected that the introduction of SWIM, which enables the *information sharing* and *CDM* concepts, will supose a major impact on the reduction of many, but not all, of the uncertainty sources. Therefore, in the long-term, a major question is which of the uncertainties will still be present (with a relatively important impact) in the ATM system.

Taking into account the simplified ATM model that has been considered in this research, the following categorization of uncertainties, together with the corresponding strategies to tackled them, have been introduced in the strategic deconfliction system finally implemented:

- *Navigational imprecision and tracking errors*, which could be tackled by adding uncertainty buffers to the SBTs/RBTs. Note that part of the uncertainty that affects the ATM system can be stated as a complementary set of trajectory parameters, which shall be quantified in a stochastic/probabilistic

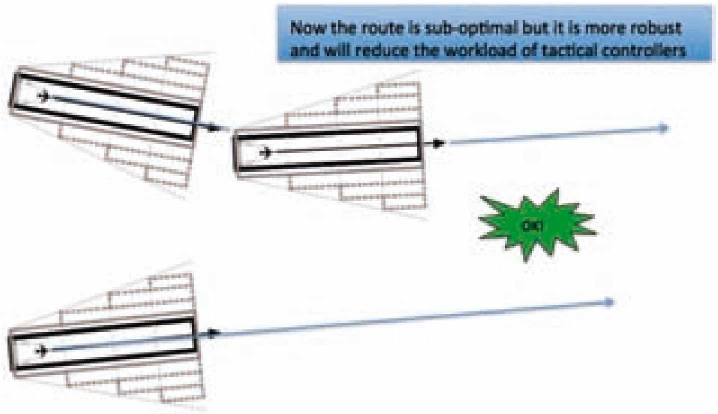


Figure A.16: A risk-of-deviation model that could be considered during strategic flight planning to reduce the number of tactical amendments

way (and according to models based on their natural physical behaviour), rather than by deterministic values. The sources of trajectory uncertainty can be either the error in the input data measurement, the error during the data processing (e.g., due to the limitations of the model) or the error in the operational practices of the airspace user, thus altogether forming the total system error (TSE) that can be fitted within a certain tolerance or buffer.

- *Individual-level perturbation*s, which refer to those unexpected events that are often caused by the AUs and that generally affect only a reduced set of trajectories, e.g., delays and/or trajectory deviations (outside of the uncertainty tolerance/buffer). A new re-allocation of all the flight routes or only of the affected ones can mitigate this problem if done in timely manner (less than 2 minutes has been achieved in this research with a regular computer). Note that the use of extra safety distance (i.e., buffer) to give tolerance for the navigational and tracking errors with a buffer-size “bigger than necessary”, can also contribute to partially give system tolerance to delays and trajectory deviations of certain dimensions (the bigger the buffer the bigger the dimensions tolerable), thus achieving a more stable flight route configuration. In this case, the trade-off between the robustness and the capacity of the system must be taken into account.

- *Network-level perturbations*, which refer to those perturbations that are often independent from the behaviour of the AUs and generally affect a large set of trajectories or even the entire network, e.g., convective weather and volcanic ash, among others. In the presence of network-level perturbations, such as a dangerous storm that forces the NM to close certain (demanded)

> airspace sectors, the complete network route allocation must be reconsidered in real time. Note that in this case, the "bigger than necessary" buffers are not helpful to mitigate the negative effects of the network-level perturbations and, in fact, the presence of these buffers can negatively contribute in these cases (especially when a demanded sector is suddenly affected by a huge capacity reduction) due to the extra space and time required in the airspace to safely allocate a certain flight trajectory. Thus, the best strategy to tackle network-level perturbations is to initiate a new Collaborative Flight Planning process in which the AUs can re-negotiate the use of the capacity actually available and adapt in consequence their airspace demand through the generation of new flight trajectories planned (and strategically de-conflicted) in real-time.

Note that the strategic de-confliction system proposed in this research is compatible with most of the current flight surveillance and tactical conflict management practices as well as with the on-board collision avoidance systems (i.e., TCAS). Thus, with the CD&R system proposed the air traffic can still be protected by three different layers of conflict management (i.e., strategic, tactical and operational) that may reduce the negative impact of uncertainty in the ATM safety levels.

Appendix B

SESAR Young Scientist Award 2012 Certificate

SESAR
JOINT UNDERTAKING

Brussels, 28th November 2012

SESAR Young Scientist Award 2012 - Nomination

SESAR Young Scientist Award Board is pleased to nominate ***Mr Sergio Ruiz Navarro*** of Universitat Autònoma de Barcelona as the Winner of the SESAR Young Scientist Award 2012.

Mr Sergio Ruiz Navarro has won the Young Scientist Award 2012 because of his quality as researcher in the SESAR WP-E project STREAM, his contribution to SWIM Master Class and his scientific contributions to the most relevant SESAR conferences including ICRAT'12, ICRAT'10, SESAR Innovation Days '11 and '12, ATACCS'11 and ATM R&D seminar. The title proposed for Mr Ruiz Navarro' PhD thesis is "Strategic 4D trajectory de-confliction to enable seamless aircraft network routes management".

SESAR Young Scientist Award Board acknowledges the relevance of Mr Ruiz Navarro's research to the thematic areas, as well as its maturity and originality. It recognises the impact of Mr Ruiz Navarro' research as demonstrated by various publications, as well as his international involvement with relevant ATM bodies in Europe.

SESAR Scientific Committee recognises this year's nomination and wishes Mr Sergio Ruiz Navarro much success in his continued PhD research.

Wishing you all the best,

Lena Martensson
Vice-Chairman SESAR Scientific Committee
Member of the SESAR Young Scientist Award Board

Figura B.1: SESAR Young Scientist Award 2012 Certificate

List of Acronyms

4D	Four Dimension
4DTRAD	4D Trajectory Datalink Services
ADS-B	Automatic Dependent Surveillance - Broadcast
ALG	Advanced Logistics Group
AMAN	Arrival MANager
ANS	Air Navigation Services
ANS	Air Navigation Services
ANSP	Air Navigation Service Provider
ASAS	Airborne Separation Assurance System
ASM	Air Space organization and Management
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATFCM	Air Traffic Flow and Capacity Management
ATM	Air Traffic Management
AU	Airspace User
BDT	Business Development Trajectory
BR&TE	Boeing Research and Technology Europe
BT	Business Trajectory
CCD	Continous Climbing Departure
CD	Conflict Detection

CD&R	Conflict Detection and Resolution
CDA	Continous Descent Approach
CDM	Collaborative Decision Making
CFMU	Central Flow Management Unit
CNS	Communication, Navigation and Surveillance
CPDLC	Controller Pilot Data Link Communication
CPU	Central Process Unit
CR	Conflict Resolution
CTA	Controlled Time of Arrival
CTO	Controlled Time Over
CTOT	Controlled Take-Off Time
DCB	Demand and Capacity Balancing
DMAN	Departure MANager
DST	Decision Support Tool
ETD	Expected Time of Departure
FL	Flight Level
FLC	Flight Level Change
FMS	Flight Management System
FPL	Filled Flight Plan
FUA	Flexible Use of Airspace
GNSS	Global Navigation Satellite System
GOA	Geometric Optimization Approach
HAC	Heading Angle Change
ICAO	International Civil Aviation Organization
ICS	Interaction Causal Solver

INAP	Integrated Network Management and extended ATC Planning Function
LTCD&R	Long Term Conflict Detection and Resolution
MET	Meteorological services
MIPS	Millions Instructions Per Second
MTCD	Medium Term Conflict Detection
MTCD&R	Medium Term Conflict Detection and Resolution
NM	Nautical Mile
NM	Network Manager
NOP	Network Operations Plan
NP	Non-deterministic Polynomial
P-RNAV	Precision aRea NAVigation
PHARE	Programme for Harmonised ATM Research in EUROCONTROL
RBT	Reference Business Trajectory
RNAV	aRea NAVigation
RNP	Required Navigation Performance
RSDS	Relational Spatial Data Structure
RTG	Resolution Trajectory Generator
RTSDS	Relational Time-Spatial Data Structure
SBT	Shared Business Trajectory
SC	Speed Change
SCTA	Short Term Conflict Alert
SDS	Spatial Data Structure
SESAR	Single European Sky ATM Research
SS	State-Space
STCD&R	Short Term Conflict Detection and Resolution

STREAM	Strategic Trajectory de-confliction to Enable seamless Aircraft conflict Management
SWIM	System Wide Information Management
TBOs	Trajectory-Based Operations
TCAS	Traffic Collision Avoidance System
TMA	Terminal Manoeuvring Area
TMR	Trajectory Management Requirements
ToC	Top of Climb
ToD	Top of Descent
TP	Trajectory Predictor
TPAS	Test-bed Platform for ATM Studies
TSDS	Time-Spatial Data Structure
TTA	Target Time of Arrival
TTO	Target Time Over
TTOT	Target Take-Off Time
UAB	Universitat Autònoma de Barcelona
UDPP	User Driven Prioritization Process
WP-E	Work Package E
WPE	Wind Prediction Errors

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