Universitat Autònoma de Barcelona

A Decision Support System based on Constraint Programming and Airspace Digitalization for Cooperative Flight Departures to improve ATM network service competitiveness

Nina Rebecca Schefers

ADVERTIMENT. L'accés als continguts d'aquesta tesi doctoral i la seva utilització ha de respectar els drets de la persona autora. Pot ser utilitzada per a consulta o estudi personal, així com en activitats o materials d'investigació i docència en els termes establerts a l'art. 32 del Text Refós de la Llei de Propietat Intel·lectual (RDL 1/1996). Per altres utilitzacions es requereix l'autorització prèvia i expressa de la persona autora. En qualsevol cas, en la utilització dels seus continguts caldrà indicar de forma clara el nom i cognoms de la persona autora i el títol de la tesi doctoral. No s'autoritza la seva reproducció o altres formes d'explotació efectuades amb finalitats de lucre ni la seva comunicació pública des d'un lloc aliè al servei TDX. Tampoc s'autoritza la presentació del seu contingut en una finestra o marc aliè a TDX (framing). Aquesta reserva de drets afecta tant als continguts de la tesi com als seus resums i índexs.

ADVERTENCIA. El acceso a los contenidos de esta tesis doctoral y su utilización debe respetar los derechos de la persona autora. Puede ser utilizada para consulta o estudio personal, así como en actividades o materiales de investigación y docencia en los términos establecidos en el art. 32 del Texto Refundido de la Ley de Propiedad Intelectual (RDL 1/1996). Para otros usos se requiere la autorización previa y expresa de la persona autora. En cualquier caso, en la utilización de sus contenidos se deberá indicar de forma clara el nombre y apellidos de la persona autora y el título de la tesis doctoral. No se autoriza su reproducción u otras formas de explotación efectuadas con fines lucrativos ni su comunicación pública desde un sitio ajeno al servicio TDR. Tampoco se autoriza la presentación de su contenido en una ventana o marco ajeno a TDR (framing). Esta reserva de derechos afecta tanto al contenido de la tesis como a sus resúmenes e índices.

WARNING. The access to the contents of this doctoral thesis and its use must respect the rights of the author. It can be used for reference or private study, as well as research and learning activities or materials in the terms established by the 32nd article of the Spanish Consolidated Copyright Act (RDL 1/1996). Express and previous authorization of the author is required for any other uses. In any case, when using its content, full name of the author and title of the thesis must be clearly indicated. Reproduction or other forms of for profit use or public communication from outside TDX service is not allowed. Presentation of its content in a window or frame external to TDX (framing) is not authorized either. These rights affect both the content of the thesis and its abstracts and indexes.

DISSERTATION

A Decision Support System based on Constraint Programming and Airspace Digitalization for Cooperative Flight Departures to improve ATM network service competitiveness

Author:

Nina Rebecca Schefers

Thesis advisor:

Dr. Juan José Ramos González

A thesis submitted in partial fulfillment of the

requirements for the degree of

Doctor in Philosophy

Electrical and Telecommunication Engineering Program

Telecommunications and Systems Engineering Dept.

Universitat Autònoma de Barcelona

Barcelona, Spain

September 2018

Dated: September 2018

Dr. Juan José Ramos González, Associate professor at the School of Engineering at Universitat Autònoma de Barcelona,

CERTIFIES:

That the doctoral thesis entitled ”**A Decision Support System based on Constraint Programming and Airspace Digitalization for Cooperative Flight Departures to improve ATM network service competitiveness**”, presented in partial fulfilment of the requirements for the reception of the degree of Doctor in Philosophy, embodies original work done by **Nina Rebecca Schefers** under his supervision.

Research supervisor:

Dr. Juan José Ramos González
Logistics and Aeronautics Unit
Department of Telecommunications
and Systems Engineering
Universitat Autònoma de Barcelona

Dedication

Thank you to my family and friends who encouraged and supported me during all this time and my academic adviser who inspired and guided me in this process.

-Nina Rebecca Schefers

Table of contents

I. List of tables

II. List of figures

III. List of acronyms

Acronyms	***Meaning***
4D or 4DT	Trajectory described in terms of 3 spatial dimensions and time stamps 4-dimensional trajectories
AI	Artificial Intelligence
ANSP	Air Navigation Service Provider
ATFM	Air Traffic Flow Management
ATFCM	Air Traffic Flow and Capacity Management
ATC	Air Traffic Control
ATM	Air Traffic Management
AU/AUs	Airspace user/ users
CSP	Constraint Satisfaction Problem
CDM	Collaborative Decision Making
CD&R	Conflict Detection and Resolution
CP	Constraint Programming
CSP	Constraint Satisfaction Problem
CTOT	Calculated Take-Off Time
DA	Data Analytics
DDR2	EUROCONTROL Demand and Data Repository
DST	Decision Support Tools
ECAC	European Civil Aviation Conference
ETOT	Estimated Take-off Time
FL	Flight Level
FMS	Flight Management System
JJSP	Job Shop Scheduling Problem
NM	Nautical Miles
RBT	Reference Business Trajectory
SDS	Spatial Data Structure
SESAR	Single European Sky ATM Research
SOCSP	Single Objective Optimization Constrained Scheduling Problem
STAM	Short-Term ATFCM Measures
SWIM	System Wide Information Management
TBO	Trajectory Based Operations
TMA	Terminal Manoeuvring Area
TP	Trajectory Prediction
TTA	Target Time of Arrival

IV. Abstract

Executive summary

The research work carried out in this dissertation proposes a new mechanism to apply a strategic shifting of Estimated Take-Off Times within their Calculated Take-Off Time Windows to reduce the probability of Air Traffic Controllers interventions.

This dissertation focuses on improving the air traffic dynamic demand capacity balance by using means of the prompt identification of concurrence events at network level, the analysis of spatio-temporal interdependencies and the mitigation of the detected concurrence events. These measures can be considered as short-term Air Traffic Flow and Capacity Management (ATFCM) measures that could be applied at local level that could reducing traffic peaks for the whole European airspace. The underlying philosophy is to capitalise present freedom degrees between layered Air Traffic Management (ATM) planning tools that sequence departures at airports. The work contributes to the well-accepted and widely spread research topic Trajectory Based Operation (TBO) that enhances the design of new Decision Support Tools (DST). The dissertation is aligned with a European H2020 Research project called "Partake".

The main contributions of the Doctoral Thesis is the development and implementation of a consecutive methodology for detecting concurrence events, analysing the trajectory interdependencies and using a mitigation method based on Constraint Programming to determine the Estimated Take-Off Time shifts. Furthermore, the doctoral thesis includes a strong experimental component focusing on validating the set of tools and its application to a realistic scenario located in the London Terminal Manoeuvring Area.

This research topic follows to some extend my study background Logistics because the European Air Traffic Management (ATM) system has to be competitive in the way to support the Airspace User (AU's) demands up to a certain point e.g. satisfying the right time (e.g. departure slots), the right costs (e.g. suitable level of Air Traffic Control (ATC) service), the right place (e.g. AU's preferred trajectories) and the right service quality (e.g. safety) without extra investments, just by removing the ATM non-added-value operations that indirectly impact on present ATM capacity. Furthermore, when looking at the explained synchronization problem it follows a similar approach as the Job Shop Scheduling Problem that represents a well-known optimization problem in the field of computer science, operation research and logistics by considering the available airspace cells as the existing resource and the aircraft as the jobs that should be performed requiring this resource.

Keywords: Air Traffic Management; Trajectory Based Operations; Decision Support Tool; Constraint Programming; Uncertainties; Conflict Detection and Resolution; Reference Business Trajectories;

Resumen Executivo

El trabajo de investigación llevado a cabo en esta disertación propone un nuevo mecanismo para aplicar un cambio estratégico de tiempos estimados de despegue dentro de su ventana de tiempo de despegue calculado para reducir la probabilidad de intervenciones de los controladores de tránsito aéreo.

Esta disertación se centra en mejorar el equilibrio de la capacidad de demanda dinámica del tráfico aéreo mediante la identificación rápida de eventos de concurrencia a nivel de red, el análisis de las interdependencias espacio-temporales y la mitigación de los eventos concurrentes detectados. Estas medidas pueden considerarse como medidas a corto plazo de flujo de tráfico aéreo y gestión de la capacidad, que podrían aplicarse a nivel local y podrían reducir los picos de tráfico en todo el espacio aéreo europeo. La filosofía subyacente es capitalizar los grados de libertad presentes entre las herramientas de planificación de la gestión del tráfico aéreo estratificadas que ordenan las salidas en los aeropuertos. El trabajo contribuye al tema de investigación bien aceptado y ampliamente difundido “Trajectory Based Operation (TBO)” que mejora el diseño de nuevas herramientas de soporte de decisiones. La disertación está alineada con un proyecto europeo de investigación H2020 llamado "Partake".

Las principales contribuciones de la Tesis Doctoral es el desarrollo y la implementación de una metodología consecutiva para detectar eventos de concurrencia, analizar las interdependencias de la trayectoria y utilizar un método de mitigación basado en la Programación de Restricciones para determinar los turnos estimados del tiempo de despegue. Además, la tesis doctoral incluye un fuerte componente experimental centrado en la validación del conjunto de herramientas y su aplicación a un escenario realista ubicado en el Área de maniobras del terminal de Londres.

Este tema de investigación sigue en cierta medida mi historial de estudios Logística porque el sistema de Gestión del tránsito aéreo europeo tiene que ser competitivo en el camino para apoyar las demandas del usuario del espacio aéreo hasta cierto punto, para satisfacer el tiempo correcto (por ejemplo, ranuras de salida), los costos correctos (por ejemplo, nivel adecuado del servicio de control de tránsito aéreo), el lugar correcto (por ejemplo, las trayectorias preferidas de usuarios del espacio aéreo) y la calidad de servicio adecuada (por ejemplo, seguridad) sin inversiones eliminando las operaciones de valor agregado sin cajero automático que tienen un impacto indirecto en la capacidad actual del cajero automático. Además, al analizar el problema de sincronización explicado, sigue un enfoque similar al problema de programación de taller que representa un problema de optimización bien conocido en el campo de la informática, la investigación operativa y la logística considerando las celdas de espacio aéreo disponibles como el recurso existente y el avión como los trabajos que se deben realizar que requieren este recurso.

Palabras clave: Air Traffic Management; Trajectory Based Operations; Decision Support Tool; Constraint Programming; Uncertainties; Conflict Detection and Resolution; Reference Business Trajectories;

Resum executiu

El treball de recerca dut a terme en aquesta tesi proposa un nou mecanisme per aplicar un desplaçament estratègic dels temps estimats enlairament dins del seu temps de desplaçament calculat finestra de temps per reduir la probabilitat d'intervencions de controladors de trànsit aeri.

Aquesta tesi es centra en la millora del saldo dinàmic de la demanda de trànsit aeri mitjançant l'ús de la identificació ràpida d'esdeveniments concurrents a nivell de xarxa, l'anàlisi de les interdependències espai-temporals i la mitigació dels esdeveniments de concurrència detectats. Aquestes mesures es poden considerar com a mesures a curt termini per a l'administració de cabal i de capacitat de trànsit aeri, que podrien aplicar-se a nivell local que podria reduir els pics de trànsit de tot l'espai aeri europeu. La filosofia subjacent és aprofitar els graus de llibertat actual entre les eines de planificació de la gestió del trànsit aeri (capes aeronàutiques) en capes que ordenen sortides als aeroports. El treball contribueix al tema de recerca ben acceptat i àmpliament difós Trajectòria basada en l'operació que millora el disseny de noves eines de suport a la decisió. La dissertació està alineada amb un projecte europeu H2020 Research anomenat "Partake".

Les principals contribucions de la tesi doctoral són el desenvolupament i implementació d'una metodologia consecutiva per detectar esdeveniments de concurrència, analitzar les interdependències de la trajectòria i utilitzar un mètode de mitigació basat en la Programació de restriccions per determinar els desplaçaments estimats del temps d'eliminació. A més, la tesi doctoral inclou un fort component experimental que es centra en validar el conjunt d'eines i la seva aplicació a un escenari realista ubicat a l'àrea de maniobra de Terminal de Londres.

Aquest tema de recerca segueix una mica més el meu fons d'estudis de logística perquè el sistema European Air Traffic Management (ATM) ha de ser competitiu en la manera de donar suport a les demandes de l'usuari de l'espai aeri fins a un cert punt, p. satisfent el moment adequat (per exemple, tragamonedas de sortida), els costos correctes (per exemple, el nivell adequat del servei de control de trànsit aeri, el lloc adequat (per exemple, les trajectòries preferides l'usuari de l'espai aeri) i la qualitat del servei adequada (per exemple, seguretat) sense inversions addicionals. eliminant les operacions de valor no agregat d'ATM que afecten indirectament la capacitat actual de l'ATM. A més, quan es mira el problema de sincronització explicat, segueix un enfocament similar al Problema de programació de la botiga de treball que representa un problema d'optimització conegut en el camp de la informàtica, la investigació operativa i la logística, considerant les cel·les de l'espai aeri disponibles com a recurs existent i l'avió com els llocs de treball que s'han de realitzar amb aquest recurs.

Paraules clau: *Air Traffic Management; Trajectory Based Operations; Decision Support Tool; Constraint Programming; Uncertainties; Conflict Detection and Resolution; Reference Business Trajectories;*

V. Acknowledgements

I would like to express my gratitude to all those, who helped me during the whole PhD research.

The PhD Program was an intensive period of intense learning and investigation that has had a great impact on me. I would like to express my deepest gratitude to my thesis supervisor Dr. Juan José Ramos González who has encouraged and led me into the academic world. Thank you for your help, patience and consistence encouragement with Constraint Programming and for giving me the opportunity to participate in a very challenging and interesting European project. I have learned a lot during the last years and I appreciate your dedication, feedbacks and guidance to achieve my research goals.

The decision to stay more years in a foreign country has not always been easy but looking back it has helped me to transform myself into a citizen of the world. I am beyond grateful for my family and my friends for accepting the distance and giving me the unconditional support and love that was necessary for this journey.

Special thanks must be given to all members of the PARTAKE project. The close collaboration was very pleasant and inspiring, and the dedication of all team members was a great contribution to the success.

Furthermore, I would like to thank the professors and members of the Department of Telecommunication and System Engineering, and all the staff of the campus of Sabadell who, at all times, were very welcoming, helpful in explaining administrative issues and always had an open ear. Thimjo and Marsel who cheered up the sometimes solitary every-day PhD life on Campus Sabadell in every possible way. Some very special thanks go to Dr. Jenaro Nosedal for introducing me to the aviation world and Marko Radanovic for being a perfect partner in crime.

Likewise, I want to convey my gratitude to the Doctoral School of the UAB. This thesis would have never been possible without the PhD research scholarship that has founded me. Also, I have been lucky to have had the support of Dr. Angel A. Juan who has encouraged me to start a PhD after my LSCM Master.

Finally, I would like to thank those, who made me feel at home while being abroad. Thank you for your friendship and the good memories.

Barcelona,
September 2018

Nina Schefers

Chapter 1

1. Introduction

Europe has some of the busiest airspace in the world, compiled from 44-member states united in the European Civil Aviation Conference (ECAC) region (ECAC 2017). To safely operate the demand, an Air Traffic Flow and Capacity Management (ATFCM) service has been established to use the given capacity to the maximum extent possible keeping in mind the guiding principles safety, continuity and expeditious for the flow of air traffic.

The main research objective of this dissertation is to reduce the probability of ATC tactical interventions due to conflicting aircraft, by developing a TBO-oriented methodology, based on identifying trajectory interdependencies and determining feasible multi-airport departure configurations that relax them. The underlying philosophy capitalises tactical flexibility of take-off times when managing departures in a multi-airport system by considering the downstream benefits of small changes on them.

To address the research objectives, first, the operational environment and the scientific foundations are explained to highlight what is the research context. Therefore, the operational environment includes an introduction to the ATM system and a scientific background that presents an introduction to Constraint Programming formalism. In a next step, the technical background reveals how the problem was solved by explaining the modular structure of the designed tools.

1.1. Introduction to ATM

The ATM System is understood as a holistic entity consisting of seven ATM conceptual components:

- Airspace organization and management
- Demand/capacity balancing
- Aerodrome operations
- Traffic synchronization
- Conflict management
- Airspace user operations
- ATM service delivery management

In order to have a well-functioning ATM system, all these components have to be present and properly integrated. In addition to the seven concept components, the exchange and management of information used by the different processes and services is of great importance.

Furthermore, the airspace organization and management provide the strategies, rules and procedures by which the airspace will be structured to accommodate the different types of air activity, volume of traffic, and different levels of service and rules of conduct. These management activities are underlined by the demand and capacity balancing that can be divided into strategic-, pre-tactical-, and tactical stages.

The problem of fitting the maximum number of aircraft into ATC sectors, keeping in mind aircraft separation and safety standards, area navigation direct routings and other factors, is known as the airspace capacity problem. Above the European airspace, a high-density network of air traffic can be found which is determined by the workload of controllers.

In Europe, an Air Traffic Flow Management (ATFM) service has been established to use the given capacity to the maximum extent possible keeping in mind the guiding principles safety, continuity and expeditious for the flow of air traffic. Demand and Capacity Balancing (DCB) strategically evaluates system-wide traffic flows and aerodrome capacities to allow Airspace Users (AUs) to determine when, where and how they operate, while mitigating conflicting needs to improve airspace and aerodrome capacity. This collaborative process allows an efficient management of the air traffic flow through the use of information on system-wide air traffic flows, weather and assets (ICAO 2005).

Within the Single European Sky program SESAR, interactive Network Capacity Planning will offer a support to stakeholders in the development of medium-term plans. Latent capacity is used to relieve bottlenecks through a consolidated capacity planning process based on coordination and network synchronisation of Air Navigation Service Provider (ANSP) enabling the adaptation of the capacity delivery where and when required (SESAR JU 2012).

The aim of the current DCB time-based measures at Network Management (NM) level is to resolve significant imbalances detected between planned traffic demand and the available network capacity by time constraining the excessive traffic demand such that the resultant traffic quantity no longer exceeds the available capacity and is presented in a smoothed flow that allows downstream ATC processes to maximise safe, flight efficient traffic throughput according to the available capacity (Sesar 2015).

To draw a connection between Air Traffic Flow and Capacity Management (ATFCM) and Air Traffic Control (ATC) as two components of the ATM, the concept of Trajectory Based Operations (TBO) was introduced. By empowering the concept of TBO as a flexible synchronization mechanism towards an efficient and competitive ATM service, a precise description of an aircraft path in space and time can be retrieved. Under this approach, airspace users should fly precise 4-dimensional trajectory (4DT) paths, previously agreed upon with the network manager and in consistency with the agreed flight plan. (ICAO 2015; Cook 2007)

Short Term ATFCM Measures (STAM) tools and functionalities rely on the TBO framework with the goal to smooth sector workloads by synchronizing the trajectory prediction to reduce traffic peaks. STAM consists of measures like minor ground delays, appropriate flight level capping and exiguous rerouting, applied on a limited number of flights after coordination, with direct effect on the workload/complexity resolution and/or delay reduction. Finally, the concept of Collaborative Decision Making (CDM) supports the above-mentioned functionalities and emphasize the coordination of processes, the sharing of accurate information among agents and the improvement of real-time data exchange between airports and the Air Traffic Flow Management (ATFM) network. This enhanced cognitive decision-making process supports the global performance ambitions for air traffic optimization.

1.2. Introduction to Constraint Programming

Constraint Programming (CP) is a powerful paradigm for representing and solving a wide range of combinatorial problems (Rossi et al. 2006). In the last few decades, it has attracted much attention among researchers due to its flexibility and its potential for solving hard combinatorial problems in areas such as scheduling, planning, timetabling and routing. CP combines strong theoretical foundations (e.g. techniques originated in different areas such as Mathematics, Artificial Intelligence, and Operations Research) with a wide range of application in the areas of modeling heterogeneous optimization and satisfaction problems. Moreover, CP nature provides other important advantages such as fast program development, economic program maintenance and efficient runtime performance. Problems are expressed in terms of three entities: variables, their corresponding domains, and constraints relating them. Constraints can be considered as the heart of CP. They are treated as logical relations among several unknowns (or variables), each taking a value from a set of accepted values called domain, which can be a range with lower and upper bounds or a discrete list of numbers. The representation of the problem, in terms of constraints, results in short and simple programs easily adaptable to future changing requirements. Furthermore, quick developing and modification of programs makes it possible to experiment with different models until the best and fastest program has been found without the programming task becoming unmanageable. This helps the programmer to concentrate only on finding the best model for the problem.

The practical benefits of CP really began to emerge when it was embedded in a programming language. Thus, CP is usually found embedded in a logic programming language, such as Prolog. In that case, it is called Constraint Logic Programming (CLP), but it does not necessarily mean that CP is restricted to CLP. Constraints can be integrated also to typical imperative languages like C/C++, e.g. COMET (Van Hentenryck & Michel 2005) or ILOG (IBM 2015), and Java, e.g. Cream (N. Tamura 2018). An example of CP embedded in a logic programming language is the CLP platform ECLiPSe (Apt & Wallace 2006). A CLP language combines:

- Logic, which is used to specify a set of possibilities to be explored by means of very simple search methods like generate-and-test, back-tracking or back-marking.
- Constraints, which are used to minimize the search by eliminating impossible alternatives in advance by the use of consistency techniques like node-consistency, arc-consistency, path-consistency or directional arc consistency.

Thus, the system combines reasoning and search. The constraints are used to restrict and guide the search. This combination is a common way of solving problems with a set of constraints to be satisfied.

Since CP is the study of computational systems based on constraints, its idea is to solve problems by stating constraints (requirements) about the problem area and, consequently, finding a solution satisfying all the constraints. This class of problems is usually termed Constraint Satisfaction Problems (CSP) and the core mechanism used in solving them is constraint propagation. Constraint propagation embeds any reasoning which consists in explicitly forbidding values or combinations of values for some variables of a problem because a given subset of its constraints cannot be satisfied otherwise (Rossi et al. 2006). In other words, constraint propagation is a way to produce the consequences of a decision.

Inference and search are in general combined in the solution process of a CSP. Trough constraint propagation, unfeasible alternatives are eliminated in advance reducing the exploration of the search space. If all the variables are instantiated after the propagation algorithm is triggered, a solution of the problem is found. Otherwise, a search process is launched through the possible assignments of values to variables, generating the whole search tree, which is an important contribution of CP is to allow the end user to control the search.

The presented approach recognises the synchronisation problem as a scheduling problem, similar to some extent to the well-known job shop scheduling problem (JSSP) or for the single objective optimisation constrained scheduling problem (SOCSP) (Tselios et al. 2013). Roughly, this problem consists of allocating the proper resources to the list of jobs facing an optimisation goal to minimise some temporal, productivity or efficiency cost function. Similar to the JSSP or the SOCSP, the available cells as portions of the airspace can be considered as the existing resource and the aircraft as the jobs that are performed requiring the resource.

In this CP model the problem is to fit all the values of the RBT. For example, the no-overlap of segments that is limited by the decision variable of the allowed green delay constraints shuld ensure the solving of all the concurrence events. In the process of satisfying all constraints while respecting the search domain, it might happen that no solution exists. There are several route interdependencies that could cause a failure due to a cycle of delays or advances in their take-off times.

To overcome this limitation, during this study the CP modelling technique *reification* was introduced to identify the occurrence of saturation. To model this problem, logical connectives between constraints are required e.g. the RBT should span over the whole duration of the flight AND one segment of the RBT must start before the next. In some cases, it is useful to apply a NOT constraint to the problem which in CSP is done by the means of reification. The reification of a constraint C produces another constraint C_r, such that C_r has an extra Boolean variable r in its variable set, and (in any solution) r is set to true if and only if the original constraint C is satisfied, see (Jefferson et al. n.d.).

1.3. Technical background

This manuscript presents an innovative Collaborative Decision Making (CDM) methodology to improve the ATM performance based on the concept of Trajectory Based Operations (TBO). The approach is innovative in the sense it proposes an integrated approach combining potential conflict detection, a novel approach to analyse trajectory interdependencies based on graph theory and a mitigation mechanism considering trajectory prediction under time uncertainty.

To detect concurrence events, the European airspace is partitioned into square cells of 6 NM representing the lateral separation minima en-route. The defined horizontal separation minimum based on radar and/or

ADS-B and/or MLAT system according to ICAO Doc 4444 (ICAO, 2016) is set to 5 NM. In this work, the horizontal separation is set to 6 NM to take into account any lateral deviations with respect to the RBT below 1 NM. It is worth to mention that the cell size is a parameter that might be changed depending on the operational context (e.g. in TMA the cell size can be set to 3NM).

A concurrence event occurs when two or more aircraft loose separation minima (vertical or horizontal). The presented approach solves the existing concurrence events applying time shifts to some of the flights. However, this aircraft take-off times shifts can generate additional concurrence events, which are called potential concurrence events. Hence for the mitigation phase the potential concurrence events, that produce critical spatio-temporal interdependencies between pairs of aircraft, must be detected.

Figure 1 illustrates the concept and shows potential concurrence events that are detected by analysing the spatiotemporal interdependencies between flights sharing the same airspace. To mitigate the concurrence events, the trajectories are shifted using slight ETOT modifications and bounded speed adjustments in such a way that a clearance is achieved.

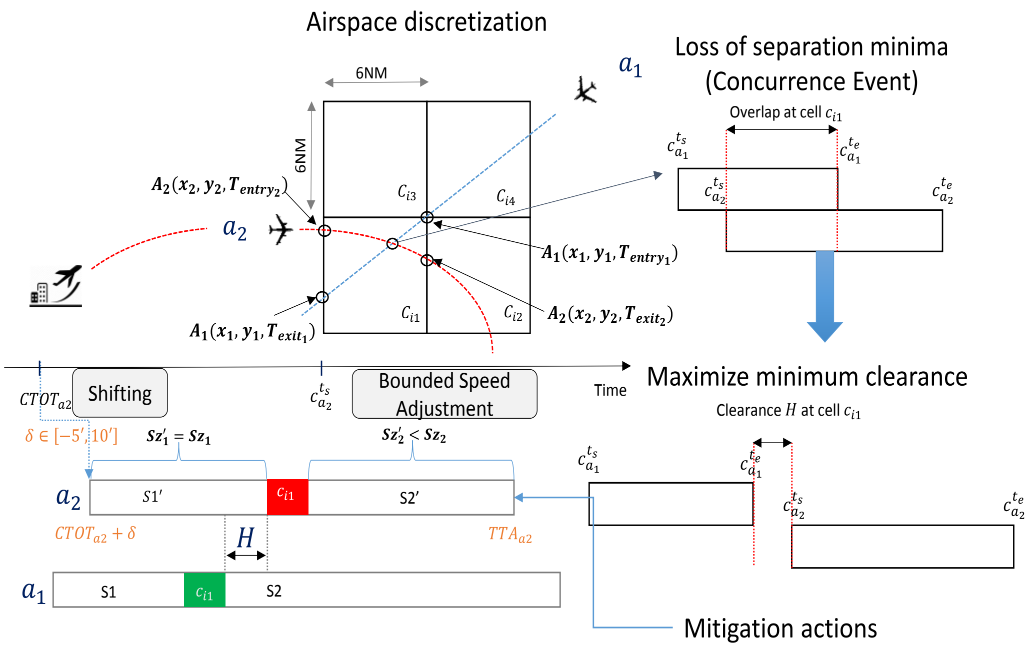


Figure 1: Overview of the proposed concept

This work shows the set of tools to determine small Estimated Take-Off Time (ETOT) adjustments within the [−5,10] minute interval along with bounded modifications on the flight duration as control actions. These actions will be calculated to mitigate the potential tight trajectory interdependencies on a multi-flight level that can emerge after inserting the traffic ready to depart.

The proposed methodology is composed of three main functionalities:

1. Detection: The detection functionality identifies the concurrence events and it is split into two sub-modules: the mapping process and the filtering process.
2. Analysis: The analysis functionality refers to the identification of topologies of interdependencies that cannot be removed by ground delays constrained by the CTOT time-window. This analysis will be helpful for identifying the trajectories that should be removed from the problem formulation in the mitigation functionality to provide a robust departure coordination.
3. Mitigation: Finally, the mitigation functionality calculates feasible time stamp domains considering multi-objective criteria to resolve the trajectory clusters.

The modular structure proposed for the development of the tools and their associated algorithms is depicted in Figure 2.

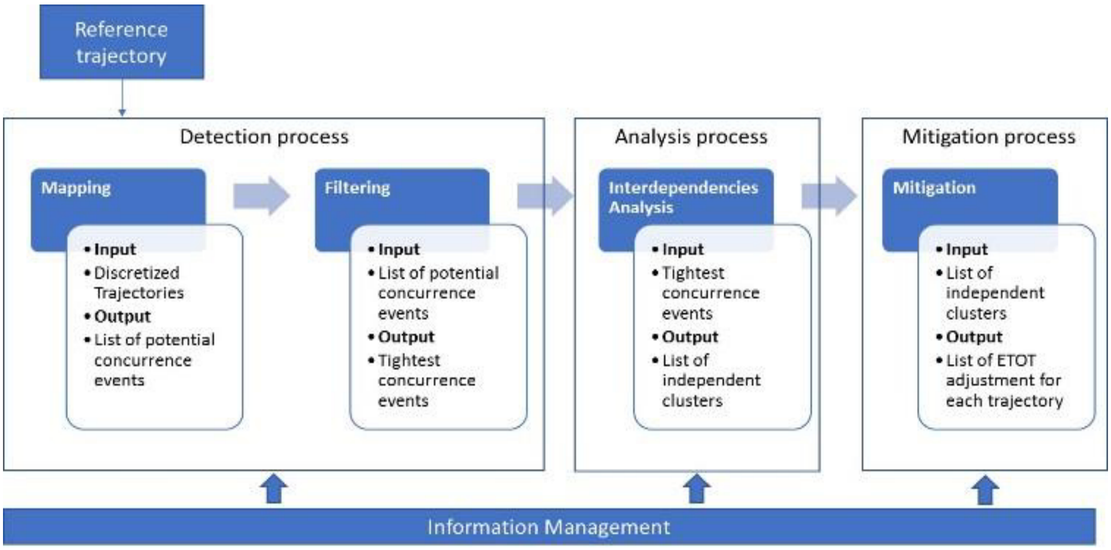


Figure 2: Modular structure of the tool

1.4. Motivation

The motivation of this thesis derives from the Air Traffic Management (ATM) Master Plan that was introduced by (SESAR 2017) to summarize essential operational and technological changes to deliver the essential contributions for the Single European Sky performance objectives (Sesar 2015). Under the framework of the TBO concept, the intention of this innovative approach is to design a competitive ATM system supporting up to a certain extent the Airspace User (AU) demands at the right time (i.e. departure slots), at the right cost (i.e. suitable level of Air Traffic Control (ATC) service) at the right place (i.e. AU's preferred trajectories) and at the right service quality (i.e. safety) without extra investments, just by removing the ATM non-added-value operations that indirectly impact on the present ATM capacity.

Aligned with the ATM mission to preserve and even improve the maximum level of safety, while achieving the maximum levels of *efficiency* and *resilience* it is broadly recognized that these challenges can only be obtained by improving the current levels of *predictability* and *flexibility*, provided by the ATM planning layers. Furthermore, AU' s shall know that any change in their initial intentions is always done to maximise the overall system efficiency driven by *fairness* and *equity* criterion. This can only be understood by the highest level of *transparenc*y.

The methodology aims to improve the present demand and capacity balance in ATM by introducing small ground delays in the programmed departure. The planned traffic is not affected since the slot time window assigned to each aircraft will be preserved. This approach allows to design a flexible TBO synchronization mechanism that preserves ATFM constraints. Furthermore, the mechanism intents to support the innovation of complexity metrics in regulation processes using advanced technologies with the aim to reduce the probability of ATC tactical interventions.

1.5. Objectives

The doctoral dissertation implements a set of tools to determine small Calculated Take-Off Time (CTOT) adjustments within the determined time-frame. Based on bibliographic sources and the research carried out, the following key research objectives of this dissertation have been defined:

Objective	Work carried out for objectives' achievement
1. Generation of operational constrains for cooperative aircraft departures using Constraint Programming formalism.	✓ Development of the CP model to determine feasible departure configurations considering time uncertainty ✓ Implementation of the optimization model

2. Improvement of the detection of tight trajectory interdependencies and the neighbourhood analysis using mapping tools.	✓ Constant improvement of TBO Mapping tools
3. Analysis of trajectory time-dependency dynamics.	✓ Graph based analysis ✓ Identification of Concurrence and Coupling Interdependencies
4. Consideration of trajectory prediction under time uncertainty	✓ Combining potential conflict detection, and a mitigation mechanism considering trajectory prediction under time uncertainty
5. Validation and verification of the proposed methods	✓ Adjustment of TBO Mapping tool towards LTMA and performance of fast simulations

Table 1: Research Objectives

1.6. List of Publications

This dissertation is based on a collection of peer-reviewed and published research papers listed below.

Principal Publications:

- Paper 1: N. Schefers, M.A. Piera, J.J. Ramos, J. Nosedal:"Causal analysis of airline trajectory preferences to improve airspace capacity", Procedia Computer Science 104, p. 321-328.
- Paper 2: N. Schefers, J.J. Ramos: "A case of a modelled saturation level for cooperative flight departures". Int. J. Simulation and Process Modelling, Vol. 13, No. 4, 2018, p. 310-323.
- Paper 3: J.J. Ramos, N. Schefers, M. Radanovic, M.A Piera, P. Folch: "A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures", 12th USA/Europe Air Traffic Management R&D Seminar, Seattle, June 2017.
- Paper 4: N. Schefers, J.J. Ramos, P. Folch, J.L Muñoz: "A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures", Transportation Research C

In addition to the above, the following paper has been elaborated and submitted during the period of research (included as appendices).

- Paper 5: N. Schefers, M.A. Amaro, J.J. Ramos, F. Saez: "STAM-based methodology to prevent concurrence events in a Multi-Airport System (MAS)", Transportation Research C (**under review**).

Complementary publications of conferences:

- Paper 6: N. Schefers, J.J. Ramos, J. Nosedal: "An efficient constraint programming model for cooperative flight departures", The International Conference on Harbour, Maritime & Multimodal Logistics M&S – HMS, 2016.
- Paper 7: N. Schefers, J.J. Ramos, P. Folch: "A decision support tool for strategic conflict management through assignment of calculated take-off times", The International Conference on Harbour, Maritime & Multimodal Logistics M&S – HMS, 2017.

1.7. Thesis structure

This thesis dissertation aims to illustrate a holistic view of the innovative main concepts that have been developed during this research and the demonstration of the behaviour of the tool in realistic traffic examples. Therefore, after the introduction in **chapter 1**, this dissertation is divided into the following chapters:

Chapter 2 outlines the current state of art. First, the current standard of metrics and decision support tools (DSTs) in the ATM domain is described. Then, the state of the art of Constraint Programming Models in ATM is illustrated.

- *Relationship to paper: N. Schefers, M.A. Piera, J.J. Ramos, J. Nosedal:"Causal analysis of airline trajectory preferences to improve airspace capacity", Procedia Computer Science 104, p. 321-328.*

As an answer to the previous mentioned research objectives, various tools were developed during this research corresponding to main functionalities (see Figure 2). **Chapter 3** presents the methodology of the tools. The description of the methodology in chapter 3 is divided as follows:

1. Conflict detection process: based on trajectories information, aircraft positions are mapped to a spatial data structure that will help the filtering and detection of trajectory interdependencies, as well as the temporal looseness at these intersections.

- *Relationship to paper:*
  N. Schefers, J.J. Ramos: "A case of a modelled saturation level for cooperative flight departures". Int. J. Simulation and Process Modelling, Vol. 13, No. 4, 2018, p. 310-323.

  N. Schefers, J.J. Ramos, P. Folch, J.L Muñoz: "A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures", Transportation Research C

2. Analysis process: the previous trajectory interdependencies are analysed using graph theory to define a set of independent sub-graphs and to be able to determine concurrence and coupling interdependencies.

- *Relationship to paper:*
  N. Schefers, J.J. Ramos, P. Folch: "A decision support tool for strategic conflict management through assignment of calculated take-off times", The International Conference on Harbour, Maritime & Multimodal Logistics M&S – HMS, 2017.

  N. Schefers, M.A. Amaro, J.J. Ramos, F. Saez: "STAM-based methodology to prevent concurrence events in a Multi-Airport System (MAS)", Transportation Research C (under review).

3. Fine take-off scheduling (mitigation) process: using a Constraint Programming paradigm, trajectories and interdependencies constraints are processed to find a slightly modified take-off schedule that will reduce the number of ATC interventions.

- *Relationship to paper:*
  N. Schefers, J.J. Ramos: "A case of a modelled saturation level for cooperative flight departures". Int. J. Simulation and Process Modelling, Vol. 13, No. 4, 2018, p. 310-323.

  N. Schefers, J.J. Ramos, P. Folch, J.L Muñoz: "A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures", Transportation Research C.

Chapter 4 shows the application of the tool and discusses the experimental results that have been obtained.

- *Relationship to paper:*
  N. Schefers, M.A. Amaro, J.J. Ramos, F. Saez: "STAM-based methodology to prevent concurrence events in a Multi-Airport System (MAS)", Transportation Research C (under review).

  N.Schefers, J.J. Ramos, P.Folch, J.L Muñoz: "A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures", Transportation Research C.

  N. Schefers, J.J. Ramos: "A case of a modelled saturation level for cooperative flight departures". Int. J. Simulation and Process Modelling, Vol. 13, No. 4, 2018, p. 310-323.

Moreover, **chapter 5-8** present the research papers and make the connection to the approaches and methodologies presented in chapter 1-4.

Finally, in **chapter 9** the conclusions and future research fields are summarized.

Chapter 2

2. State of the Art

2.1. Metrics and Decision Support Tools in ATM

The research sector of Conflict Detection and Resolution has undergone a paradigm shift from tactical to strategic ATC with the introduction of the 4D-TBO concept, representing the current state of the art of this research sector. Instead of adjusting flights just in time, the overall flight performance can be improved significantly by performing more efficient avoidance manoeuvres assuming proper forecasts (Kuenz, 2015). The benefit of the TBO concept is an accurate 4-dimensional trajectory (3 spatial dimensions and time) the aircraft will fly. The details of the trajectory will be shared by all involved parties through System Wide Information Management (SWIM). Also, intervention in the trajectory will happen in full knowledge of the downstream effects as shown in (Nosedal et al., 2015) and hence it will be possible to pick the option causing the minimum amount of trajectory distortion. Finally, the removal of most uncertainties around the trajectory, using Artificial Intelligence (AI) and Data Analytics (DA) such as predictive analytics, makes it possible to improve the airspace volume as stated in (Wilco, 2017).

Researchers have used the advantages of the 4D-TBO concept and studied, among other, conflict detection and separation observance approach as in (Ruiz, Piera and Del Pozo, 2013; Ruiz et al., 2014) or strategic trajectory planning approaches with uncertainty as in (Chaimatanan, Delahaye and Mongeau, 2018). Efficient High-Performance Conflict Detection and Resolution methods have been developed in (Kuenz, 2015) for large traffic scenarios based on an N-dimensional bisection of airspace allowing a significant reduction of complexity using the TBO concept. An initial potential conflict detection approach based on the partitioning of the airspace has been proposed by (Nosedal et al., 2014), which serves as the baseline for the present work. The work presented in this paper introduces major contributions both in detection and mitigation mechanisms with respect to the methods proposed in (Nosedal et al., 2014). As to detection mechanisms these contributions can be summarized as follows: a 3D cell-grid based method is introduced for the 4D trajectory digitalization and an intelligent pairwise analysis is implemented to avoid false negatives in the detection of the traffic through each neighbouring cell. The proposed 3D discretization enables the representation of the trajectories from departure to arrival. From the methodological perspective, full 4D trajectories are processed and the analysis is not limited to a particular phase of the flights; from the applicability perspective, the proposed technique extends its usability to TMA and not just to en-route traffic; from the practicality perspective, the technical implementation of mapping and detection processes scales to different operational contexts, with different criteria for vertical and lateral separation. Regarding the mitigation mechanisms, the model has been totally reformulated while preserving the basic idea of the CTOT shifting to remove conflicts. In summary, the Constraint Programming (CP) model presented in this paper has the following major improvements: the new decision variables represent the whole flight trajectory, which enables the removal of its potential conflicts happening at different flight levels; introduces slight speed adjustments as decision variables in order to minimize the impact of the CTOT shifting in the arrival time; the model can tackle the effect of along-track deviations, if they can be measured or estimated; finally, the new CP formulation takes advantage from propagation mechanisms of constraints such as no overlap, span and synchronize, with a very positive impact in the computational effort required to solve this combinatorial optimization problem.

Moreover, the trajectory optimization studies focusing on the sensitivity of operational costs and efficiency have been carried out in (Vilardaga et al., 2015) and a coordinated multi-aircraft 4D trajectories planning, considering the buffer safety distance and fuel consumption optimization has been studied in (Qian et al., 2017). Finally, machine learning techniques have been used recently, for example to address the short-term trajectory prediction problem in Terminal Manoeuvring Area (TMA) based on 4D trajectory prediction as in (Wang et al., 2017).

The introduction of the 4D TBO concept, furthermore allows introducing further system-level policy decision making processes such as Short-Term ATFCM Measures (STAM). STAM can involve measures like advancing or delaying aircraft by using the minor departure adjustments on the ground (referred to as green delays in (Castelli et al., 2011; Piera et al., 2014)), fight level capping, minor re-routings e.g. in (Adacher et al., 2017), linear holding e.g. in (Xu and Prats, 2017), slot allocation and sequencing methods, e.g. in (Çinar et al., 2017; Liang et al., 2017; Marcella et al., 2017), headings or speed variations which apply to a limited number of flights to reduce the complexity of the anticipated traffic peaks (Eurocontrol, 2017b). However, some manoeuvres are often not considered desirable measures by AUs due to high operational and fuel consumption costs as it was evaluated in studies of (Ferguson et al., 2013; Envisa, 2017). Green delays on the ground are therefore a more acceptable alternative which is also the mitigation measure used in this work. The concept considers the small departure time adjustments recognizing global trajectory interdependencies. The goal of STAM applications is to support the dynamic Demand Capacity Balancing (DCB) concept and therefore, to improve Air Traffic Flow and Capacity Management to enhance the ATC workload as proposed in (Masalonis et al., 2003; Netjasov et al., 2011).

Historically, the ATFCM activities have been based on metrics estimated at strategic level such as the *entry-count*, and more recently, the *occupancy* (Eurocontrol 2007). The number of aircraft that can be handled by the ATCs is limited by their workload. When the maximum capacity is about to be reached, the air traffic demand is limited by applying regulations to all the aircraft of the sector. Regulations produce delays or re-routings and have a direct impact on the environment and in the airlines strategy. From the ATM point of view, these measures are effective, because limiting the demand releases the system, but not efficient enough because it affects all the agents of the system. The results of limiting the demand is an eventual over-release of the airspace that reflects that the measures taken to avoid a likely high-demand situation were not based on a good prediction of the system. The current metrics do not provide enough detail to determine the effects of the expected demand in the ATCs workload. At this point, the DCB process requires more realistic ways to determine how an increase of the demand in a sector affects the number of ATC interventions, i.e. using machine learning and big data technologies to improve the forecasts or introducing the use of complexity metrics in the regulation process.

Complexity metrics have been studied since many years by different authors (Netjasov et al. 2011). Additionally, Air Navigation Service Providers (ANSP) could calculate their own complexity metrics to reconfigure the airspace according to the required capacity or to support the decision-makers to impose local restrictions, such as Minimum Departure Intervals (MDI) (Eurocontrol 2018). The effects of these measures tend to be efficient in areas where many airports feed a high number of aircraft to a common sector (e.g. London TMA). Although the MDI could be considered a more dynamic process, the principle is based in limiting the demand of selected Standard Instrumental Departures (SID). Consequently, equally-distributed ground delays (e.g. "one each ten minutes") are applied to all the flights that use the affected SIDs. To determine the required interval, the measure *groups* the affected flights by SID and its purpose is limiting the entry-count/occupancy to the target sector like performed at strategic level during the DCB process. The process does not identify what are the actual effects of selected flights in the target sector nor in the ATC workload.

2.1. Constraint Programming Models in ATM

Nowadays, the systems strongly rely on Artificial Intelligence (AI) and Data Analysis (DA). During the last years, supported by the introduction of the 4D-TBO concept, the application and improvement of Decision Support Tools (DST) in ATM was advanced to support the global performance ambitions for air traffic planning and optimization. From an operational research perspective, some ATM problems can be seen as decision-making problems whose resolution consists of determining the domain values of the decision variables to reach feasible solutions. Furthermore, in case an objective function is formulated to describe the benefits of each feasible solution, there are some methods that could be applied to identify the best solution. However, since ATM problems (such as re-routing, flight-level changes, or ground-holding schemes) are usually complex problems of a large dimension, and highly combinatorial, there are few AI problem-solving technologies that can cope with that many different degrees of freedom. One efficient technique is CP, which has also been used in this work to determine which aircraft CTOT should be modified within the domain of [-5,10] minutes. CP is a powerful paradigm for representing and solving a wide range of combinatorial problems (Rossi, Van Beek et al., 2006) and offers a constrained version of real world data analysis problems (Rossi et al., 2006). In the last years, the paradigm has attracted much attention among researchers because it proposes on the one hand the modelling, using a high-level programming language, and on the other hand the solving, using various techniques from different areas such as mathematics, artificial intelligence, and operations research (Van Hentenryck et al., 1992). Moreover, the nature of CP provides other important advantages such as a fast program development, an economic program maintenance and an efficient runtime performance.

Other than metaheuristic or heuristic method, such as evolutionary algorithms, CP is used to solve complex combinatorial Constraint Satisfaction Problems (CSP). CSPs are expressed in terms of three entities: variables, their corresponding domains, and constraints relating them. Constraints can be considered as the main characteristics of CP. They are treated as logical relations among several unknowns (or variables), each taking a value from a set of accepted values called domain, which can be a range with lower and upper bounds or a discrete list of numbers. Solving a CSP consists in assigning a value to each variable in such a way that every constraint is satisfied. The main interest of such a technology is the generality in the notion of what is a constraint. It enables the user to have access to a rich, high-level language that helps combine constraints together to build new ones, thus leading to an expression of the problem that is very close to its mathematical formalisation. The representation of the problem, in terms of constraints, results in short and simple programs easily adaptable to future changing requirements (Bessiere, 2006).

The application of CP is used both in scientific and industrial sectors for many kinds of application, such as scheduling or resource assignment problems. Furthermore, it has been successfully used in many research studies in the ATM field, as reported in (Allignol et al., 2012). A CP model in the ATM context that would consider all degrees of freedom (3D geometry and time) to generate an optimal set of conflict-free 4D trajectories at a continental scale is out of scope reach for the current combinatorial problem-solving technologies. In this work, the use of CP to reduce the ATC interventions by profiting of time stamps (i.e. RBTs) as a degree of freedom is proposed. Furthermore, the degree of freedom is constrained to a time window of -5 to +10 minutes of the assigned departure time and, in comparison to existing works, this approach considers a fixed part which is determined by those aircraft that are already in the air and cannot be modified. Therefore, the large-scale space of solutions is reduced to a size in which CP models could provide feasible and even quasi-optimal solutions.

Considering the ATM sources of uncertainty (parameters of aircraft models in trajectory prediction, weather, failure of ATC systems, cancellation of flights, etc.) and the degree of safety, a rolling horizon model scope is recommended to be considered in CP models to handle reasonable amounts of uncertainty. To avoid being affected by the scalability problems, the time windows should be considered small enough to take into account only a limited amount of uncertainty. Based on the classification of uncertainty sources as described in (Mondoloni, 2006; Casado et al., 2012) in which many uncertainties can be modelled as stochastic variables, (Pabst et al., 2013) proposes a method to transfer those stochastic errors to the position errors. In this work, a similar approach is presented, focusing on the weather forecast uncertainties, particularly the impact of along-track wind uncertainty.

Existing literature shows that CP in ATM is used in rolling horizons in which the ‘past’ part of the current solution is fixed, and the decision variables are considered as constants. The ‘future’ part of the problem is resolved with the new horizon. Various CP models to improve air traffic services have been developed. For example, a CP model for flight-level allocation for a vertical separation was developed in (Barnier et al., 2004) and a CP model that minimizes the number of required ATFCM regulations has been developed in (Kerlirzin et al., 2000). Models that focus on improving the ATC workload have been developed in (Trandac et al., 2005) where a CP model for an airspace sectorization is presented and in (Flener et al., 2007) a CP model to minimize and balance the traffic complexities of airspace of the adjacent sectors is proposed. Finally, (Chemla et al., 1995) laid the foundation for CP modelling of the slot allocation problems. In (Allignol et al., 2012) a better description of improvements to the slot allocation problems together with CP applications can be found. Further planning methods and decision support tools can be found in (Barnier et al., 2009) where a CP model for a conflict-free planning method is introduced and (Van Leeuwen, et al., 2003) where a CP model for decision support is presented to aid the controllers in planning the movements of flights within an airport and its airspace. The work presents a CP model to solve the problem by describing the trajectory as a sequence of the time intervals that represent the conflict-free segments and the concurrence events segments introducing a multi-flight level approach. The scheduling consists in ensuring of the non-concurrent use of the areas that were in conflict. Since the tools highly rely on an accuracy of the Trajectory Prediction (TP) to reduce the number of the en-route conflicts, the time uncertainty is considered in the approach and to complement it different flight levels are considered. This is supported by the calculation of more dynamic metrics based on short-term trajectory predictions that identifies the effects of each AU as a stand-alone element of the system. This process determines the effects of individual AUs in the number of ATC interventions by detecting the imminent and potential concurrence events of each flight that crosses the target volume. Then, a small changes of the Estimated Take-Off Time (ETOT) of selected flights in order to reduce the probability of ATC interventions is proposed.

Chapter 3

3. Methodology

The main objective of the presented methodology is to enhance the airspace demand-capacity balance by trying to reduce the potential air traffic controller interventions en-route. Towards this goal, tight interdependencies between aircraft trajectories are identified at the network level and are removed by rescheduling take-off times in such a way that target times of arrival are preserved within a one-minute margin. This can be seen as a short term ATFCM measure that enables a slight increase in airspace capacity by transferring the workload of controllers from conflict resolution and manoeuvre communication to traffic monitoring.

The proposed concept is composed of three main functionalities: detection, analysis, mitigation. To this aim, trajectories are mapped on a grid of cells and filtered to identify only the tightest concurrence events. A trajectory interdependency exists when two or more aircraft share a similar set of spatiotemporal coordinates. Subsequently, the trajectory interdependencies are classified and analysed using a causal model that identifies a set of timestamp domains defined to highlight the weaknesses of the system. Lastly, the most relevant interdependencies are mitigated by producing a delay or advance of their Estimated Time of Take-Off (ETOT) for some selected flights linked to the tightest interdependencies.

3.1. Detection Methodology

The conflict detection is composed of two processes: the mapping process and the spatiotemporal interdependency detection. The concurrence event detection methodology is designed to detect concurrence events in different flight levels (FL). In comparison to existing concurrence event detection models, our approach does not only identify pairwise conflicts but interdependencies between trajectories that lose their safety buffer. The benefits of this methodology are the efficient way of identifying concurrence events in air, the possibility to understand the impact of the trajectory interdependencies and to apply mitigation measures.
In the following, the three processes for the 3D concurrence event detection are described.

3D Mapping Process

To detect concurrence events, the European airspace covering the longitude of -20 to 30 degrees and latitudes of 0 to 80 degrees, is partitioned into square cells of 6 NM representing the lateral separation minima en-route. The defined horizontal separation minimum based on radar and/or ADS-B and/or MLAT system according to ICAO Doc 4444 (ICAO 2016) is set to 5 NM. In this work, the horizontal separation is set to 6 NM to take into account any lateral deviations with respect to the RBT below 1 NM. It is worth to mention that the cell size is a parameter that might be changed depending on the operational context (e.g. in TMA the cell size can be set to 3NM). Taking advantage of the 4D-TBO concept that is based on the integration of time into the 3D aircraft trajectory, 4D trajectories are project onto the grid. The benefit of working with 4D trajectories is that this concept ensures that the aircraft can fly on a practically unrestricted, optimum trajectory for as long as possible in exchange of the aircraft being obliged to meet very accurately any arrival time over a designated point (SKYbrary 2017). As a result of the mapping projection a 4D trajectory is partitioned in segments, one for each cell the trajectory occupies. All the generated segments are stored in a matrix representing the grid, whose size depends on the cell size and vertical separation to be considered. The segments are stored as a sequence of two or more 4D points containing latitude, longitude, time and flight level. The first point in the sequence is the entry point in the cell and the last is the exit point.

To achieve a multi-level mapping an aircraft a_i that changes its flight level from flight level FL_i to FL_{i+1}, will be represented on both flight levels during its climbing/descend manoeuvre. Applying this method, it might occur that a concurrence event for aircraft a_i is registered in several fight levels because it is actually performing a climbing or descend manoeuvre, so it might happen that several concurrence events involving the same aircraft are detected simultaneously at the different flight levels. This is a rather conservative but safe approach which is the most important factor in air traffic management. A graphical illustration of the method used to detect concurrence events on a 3D level is represented in Figure 3.

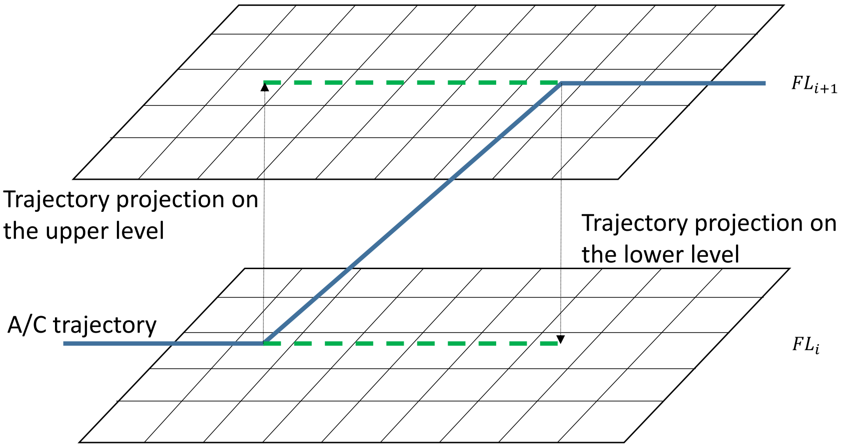


Figure 3: 3D Multi-flight level mapping

Spatio-Temporal Interdependency detection

A concurrence event occurs when two or more aircraft loss the separation minima (vertical or horizontal). The presented approach solves the existing concurrence events applying time shifts to some of the flights. However, this aircraft take-off times shifts can generate additional concurrence events, which are called potential concurrence events. Hence for the mitigation phase the potential concurrence events, that are the critical spatio-temporal interdependencies between pairs of aircraft, must be detected.

The detection of spatio-temporal interdependencies is performed by calculating the temporal looseness ("clearance time" or "overlap time") between a pair of aircraft segments in the same cell (see Figure 4). The temporal looseness H of two aircraft can be calculated by determining the minimum value of the exit time of the two aircraft minus the maximum entry time. To be considered as a potential concurrence event the temporal looseness H of a pair must satisfy:

$$H = min\left(c_{a_1}^{t_e}, c_{a_2}^{t_e}\right) - max\left(c_{a_1}^{t_s}, c_{a_2}^{t_s}\right) \geq -h_m = (\delta_M - \delta_m) \qquad (1)$$

Where δ_M is the maximum slot time shifting that can be applied (e.g. 10 min), and δ_m the maximum advanced time (e.g. -5 min), $c_{a_i}^{t_s}$an refers to the time of an aircraft a_i entering into the cell and correspondingly, $c_{a_i}^{t_e}$ refers to the time of the aircraft leaving the cell c. When $H \leq 0$ there is a clearance, and when $H > 0$ there is an overlap. For instance, if the domain for rescheduling the CTOT is set to [-5, 10] minutes, the greatest value of H to consider a pair of aircraft as a potential concurrence event is 15 minutes (900 seconds). Therefore, the list of the tighter spatio-temporal interdependences must be filtered with $h_m = 15$ minutes, the maximum CTOT shifting window which would not endanger the safety separation even if the shift at each interval end is applied to each aircraft.

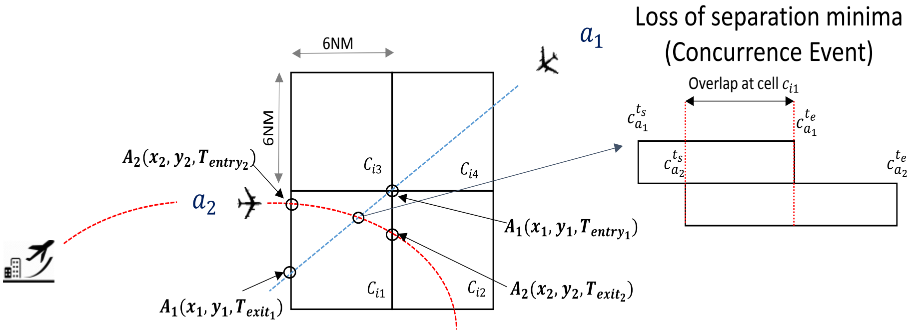


Figure 4: Spatio-temporal interdependency registration

It may happen that two or more aircraft are flying at two neighbouring cells losing the separation minima, so cell occupancy check will miss those potential concurrence events. To ensure the reliability of the potential concurrence event identification, the traffic in the surrounding cells of each cell j is analysed using an intelligent neighbourhood check in order to properly detect any loss of separation. The algorithm takes for each occupied cell j all its surrounding cells that have at least one aircraft inside. Then the H value is computed for all possible pairs of aircraft that are in cell j and in the neighbourhood, an all those pairs that have and $H > 900$ are discarded. For the rest of the pairs, the minimum distance between the segments is calculated and compared with the threshold value (6NM). The Figure 5 illustrates how this process will detect the loss of separation between Ac_1 and Ac_2 in cell j and cell i_7. This verification is performed for each occupied cell in the grid.

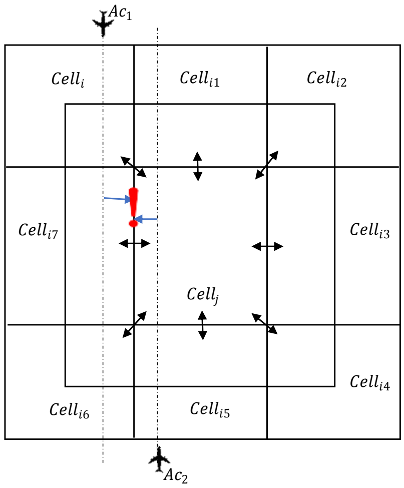


Figure 5: Neighbourhood analysis

The algorithm checks all the cells in the grid, and if the occupancy of the cell j is greater than zero then the temporal looseness is computed for all the pairs of segments inside the cell j, as well as all the possible pairs that have one segment in the cell j and its neighbouring cells. For those pairs that have one of the segments out of the cell j with $\mathrm{H} \geq -\mathrm{h_m}$, the algorithm also computes the minimum distance. Hence, the computational effort of the algorithm depends on the grid size (number of cells) and, more relevant, on the distribution of the trajectory segments in the grid, since the combinatorial part of the algorithm appears in the neighbourhood pairwise analysis when all the possible pairs are checked. Nevertheless, computational times are very competitive when analysing realistic, or even stressed, traffic. This is because it doesn't make sense to decrease the cell size arbitrarily and also because of the traffic density in a given area is limited by the ATM capacity, so the pairwise analysis does not create any combinatorial explosion. Furthermore, the proposed algorithms can be easily parallelized in order to make neglectable the detection computational time in any practical application.

3.2. Analysis methodology

The second module of the methodology is the Analysis tool. After the mapping and filtering process, several sets of pairwise potential concurrence events could be obtained. Using graph theory, the potential concurrence events detected in one cell at the same FL will form a node or vertex of a graph G and its edges will represent the interdependencies between potential conflicts.

After detecting the concurrence events, a set of trajectory interdependencies over the terminal airspace is represented. The output represents all concurrence events as being interrelated. The objective is to decompose the complex problem that is a conjunction of a huge amount of S-T interdependencies to reduce the complexity, see Figure 6.

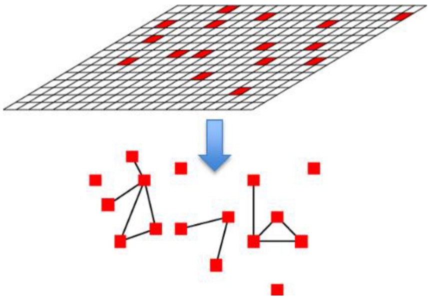


Figure 6: Illustration of interdependencies using graph representation

Then, the potential conflicts are grouped by cells and by flight level in order to identify clusters of potential conflicts that share a physical location in the space. Once the clusters are made, it is distinguished the pairwise conflicts that produces a unique potential concurrence event using time information. This step transforms the spatial representation of the potential conflicts induced by the grid into a A-dimensional representation, see Figure 7.

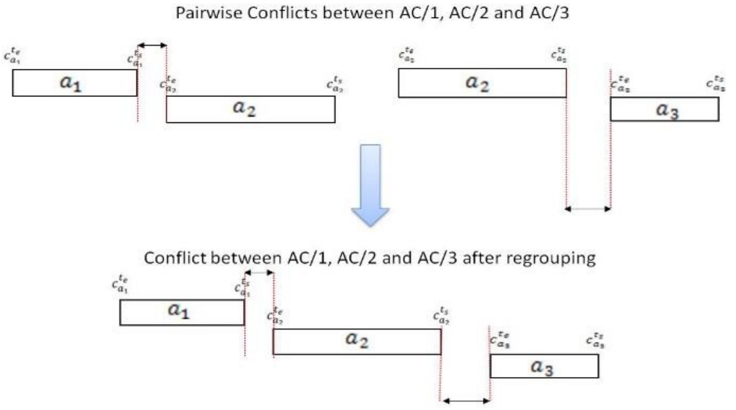


Figure 7: Regrouping two pairwise conflicts to form one conflict node

All the nodes in graph G are outputs of this procedure, thus, one node, which represents one potential conflict, could involve more than one aircraft. Furthermore, two different nodes may represent two potential concurrence events in the same cell, but involving different aircraft in different time.

To construct G it is defined also the edge set $E(G)$. As aforementioned, the edges in G must represent the interdependencies between potential concurrence events and the rescheduled takes-off times. Hence, edges must be related to RBTs of the aircraft involved in the nodes of G. It is added and edge of uv to $E(G)$ if and only if there is at least one aircraft involved in node u and in node v. That is an edge $uv \in E(G)$ if and only if u and v shares an aircraft.

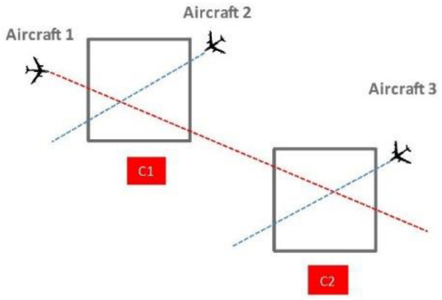


Figure 8: Two potential conflicts sharing aircraft 1

Figure 8 shows two potential concurrence events that occur in different cells. Let be u the node of G that represents the potential conflict listed in cell c_1 and v the node for the conflict in c_2. Then, it is added the edge uv to $E(G)$ because u and v share Aircraft 1.

The problem is represented by taking advantage of the adjacency list and the adjacency matrix. For the traversal graph, also known as graph search, the Depth-First Search (DFS) algorithm is used. By formulating the problem using graph theory, the whole function can be decomposed to find a set of disconnected graphs that form independent clusters, as shown in Figure 9.

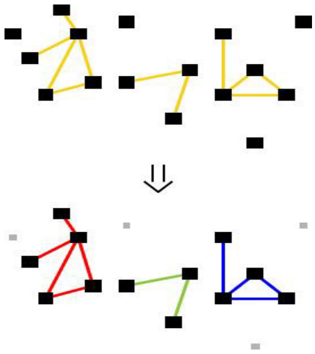


Figure 9: Independent clusters

Moreover, graph representation allows identifying concurrence and coupling interdependencies. Concurrence interdependencies are those which appear between aircraft that are in the same node in G, see Figure 10.

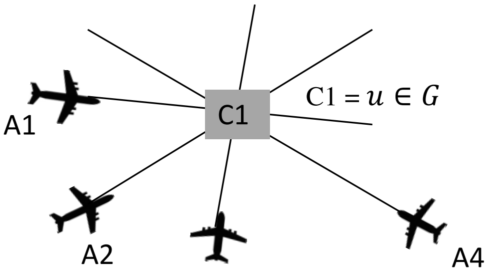


Figure 10: Concurrence interdependencies

If there exist in G a uv-path between two nodes u and v each one encoding a potential conflict, then there is a coupling interdependence between them, see Figure 11.

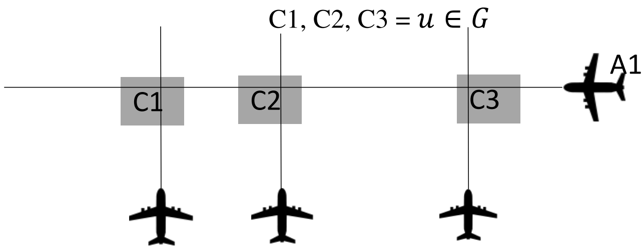


Figure 11: Coupling Interdependencies

The introduction of coupling and concurrence interdependencies allows it to define metrics to understand when an aircraft should be delegated or eliminated of the solution space.

Finally, when rescheduling take-off times, the potential concurrence event encoded in u may result in a reduction of the clearance H in v by modifying the CTOT of Aircraft 1 and vice-versa. In cases where u and v represent potential conflicts with a positive clearance H in both cases, a rescheduling take-off in Aircraft 1 may remove one potential conflict but, produce at same time a real conflict later on. The formulation based on graph theory allows to represent real conflicts and their interdependencies and to visualize the complex structures.

Once the interdependent clusters are detected, the mitigation tool based on constraint programming can be supported. By partitioning the problem size, better computational performance and the reduction of the probability of ATC interventions due to greater clearance times could be achieved, which directly enhances the airspace demand-capacity balance.

3.3. Mitigation Methodology

The mitigation algorithm shall be formulated as an optimization problem where the constraints are formulated to remove the tight interdependencies (H>0). The mitigation tool is based on the following modelling structures.

A set of aircraft

C set of cells that have a concurrence event

F set of Flight Levels

$$C_A^F = \{< c, a, f > \mid \forall c \in C, \forall a \in A, \forall f \in F\} \tag{2}$$

$$RBT_a = \{\hat{g}_i^{a_f}\}, \qquad i = 1..p(a) \tag{3}$$

d.v. $\delta_a \in [-\delta_{min}, \delta_{max}], \forall a \in A$ (4)

d.v.$P_{c_{a_f}}: sz\left(P_{c_{a_f}}\right) = \left((c_{a_f}^{te} + p_w(t_e)) - (c_{a_f}^{ts} + p_b(t_s))\right), \forall c_{a_f} \in C_{A_F}$ (5)

d.v. $O_c = \left\{P_{c_{a_f}} \middle| c_{a_f} \in C_{A_F}\right\}, \ \forall c \in C, \forall f \in F$ (6)

d.v. $G_a = [s_a, e_a)$ (7)

d.v. $g_i^{a_f} = [s\left(g_i^{a_f}\right), e\left(g_i^{a_f}\right)\right), \forall a \in A, \forall f \in F, \forall i \in 1..p(a)$: (8)

$$sz\left(g_i^{a_f}\right) \in [sz\left(\hat{g}_i^{a_f}\right) - l\left(\hat{g}_i^{a_f}\right), sz\left(\hat{g}_i^{a_f}\right) + l\left(\hat{g}_i^{a_f}\right)]$$

d.v. $T_a = \left\{g_i^{a_f} \mid \forall a \in A, \forall f \in F, i \in 1..p(a)\right\}$ (9)

Minimize:

$$w_1 \sum_{a=1}^{n} |\delta_a| + w_2 \sum_{a=1}^{n} L(G_a) \tag{10}$$

subject to:

$$s\left(P_{c_{a_f}}\right) = (c_{a_f}^{ts} + p_w(t_s)) \pm \delta_a \tag{11}$$

$$\forall P_{c_i}, P_{c_j} \in O_c \tag{12}$$

$$NO(O_c) \Leftrightarrow \pi(P_{c_i}) < \pi(P_{c_j}) \Rightarrow e(P_{c_i}) \leq s(P_{c_j})$$

$$s(G_a\,) = CTOT_a \pm \delta_a \tag{13}$$

$$e(G_a\,) \in [TTA_a - 1, TTA_a + 1] \tag{14}$$

$$span\left(G_a, \{g_i^{a_f}\}\right), \forall a \in A, \forall g_i^{a_f} \in T_a \tag{15}$$

$$\forall a \in A, \forall f \in F, \forall i, j \in 1..p(a)$$

$$NO(G_a) \Leftrightarrow \pi(g_i^{a_f}) < \pi(g_j^{a_f}) \Rightarrow e(g_i^{a_f}) \leq s(g_j^{a_f}) \tag{16}$$

$$e\left(g_i^{a_f}\right) \leq s\left(g_j^{a_f}\right), \forall i, j\colon i < j \tag{17}$$

$$e\left(g_i^{a_f}\right) = s\left(g_j^{a_f}\right), \forall i, j\colon j = i + 1 \tag{18}$$

$$\begin{cases} s\left(g_i^{a_f}\right) = s(P_{c_{a_f}}) \\ e\left(g_i^{a_f}\right) = e(P_{c_{a_f}}) \end{cases} \Leftrightarrow \begin{matrix} s\left(\hat{g}_i^{a_f}\right) = c_{a_f}^{ts} \\ e\left(\hat{g}_i^{a_f}\right) = c_{a_f}^{te} \end{matrix}, \forall c_{a_f} \in c_{A_F} \tag{19}$$

$$synchronize\left([g_i^{a_{f_i}}], \left\{g_i^{a_{f_j}}\right\}\right), \forall g_i^{a_f} \in T_a \tag{20}$$

Table 2: CP data structure

The CP model data structure defines a set of aircraft A and a set of concurrence event cells C at a given flight level F.

The decision variables ensure that the departure adjustment of the aircraft remains in the defined timeframe of [-5,10] minutes (equation 4); the interval for the occupancy of the cell c by an aircraft a at a given FL f with its size and start and end time (equation 5); each of the cells can be occupied by one aircraft at a certain FL at a time, so the aircraft going through the cell must be sequenced accordingly (equation 6); the representation of the entire flight trajectory where s_a will be the take-off time and e_a the arrival time in the solution (equation 7); the interval variables representing the segments of the G_a and their size (equation 8); and the sequence variable T_a is introduced to set the relationship between the trajectory segments g_i^a and the entire trajectory G_a (equation 9).

The bi-objective optimization goal that combines the aspects w_1 (minimizing the total aircraft delays) and w_2 (binding the Target Time (TT); where a refers to the aircraft, δ_a is the delay applied and $L(G_a)$ represents the minimization of all RBT segments according to their allowed elasticity if the TT cannot be met), see equation 10.

The first constraint aims to model the shifting of every interval variable $P_{c_{a_f}}$ according to the applied delay and its time-uncertainty (equation 11). Furthermore, all aircraft in a cell c with proximate events should have no overlap (equation 12). The interval variable G_a which represents the duration of the flight is determined by the constraint of the take-off time (equation 13) and the time of arrival (equation 14). Furthermore, the relationship between the flight interval variable and its segments is modelled by the following *span* condition to ensure the completeness of the trajectory (equation 15). The constraint *span* states that the interval flight spans over all present intervals from the set segments. That is, interval flight G_a starts together with the first present segment interval and ends together with the last one. To ensure this, the *no overlap* constraint (equation 16) ensures that interval variables to not overlap each other. In this case, the individual Reference Business Trajectory (RBT) segments should have no overlap. Also, the constraint is added that ensures that one segment has to start before the next (equation 17) and that the start of segment j takes place after the end of segment i (equation 18). Equation 20 is used to link the interval variable $P_{c_{a_f}}$ that is used in combination with the sequence variable O_c to remove the concurrence events at cell c, with the concurrence segments of the trajectory T_a, since they are representing the same time windows. Finally, (equation 20) synchronizes the trajectory segments of different FLs to model the 3D concurrence event mitigation. (Schefers et al. 2016)

3.4. Relationship to papers

The described methodology has been presented in various journal and conference papers. The focus of the paper

N. Schefers, J.J. Ramos: "A case of a modelled saturation level for cooperative flight departures". Int. J. Simulation and Process Modelling, Vol. 13, No. 4, 2018, p. 310-323

has been to develop and apply the detection methodology and the mitigation model based on Constraint Programming. In this paper it can be observed that the detection tool contains a sequence of processes to detect concurrence events and that the Constraint Programming model focusses on the introduction of segments to represent the entire RBT to reach the TTA by introducing speed adjustments. During this research study, the methodology has been further improved and refined. In the paper:

N.Schefers, J.J. Ramos, P.Folch, J.L Muñoz: "A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures", Transportation Research C.

it can be observed that the detection process has been improved to be more efficient. The paper represents the latest progress of this research. In fact, a powerful detection tool has been designed that is able to detect concurrence events in a 2h traffic sample within seconds. Furthermore, the dimensions have been extended towards considering Multi-Flight-Levels. The CP model also has been extended supporting speed adjustments, Multi-Flight-Levels and time uncertainty. The time uncertainty approach also has been improved during this research. First findings are documented in the paper:

J.J. Ramos, N. Schefers, M. Radanovic, M.A Piera, P. Folch: "A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures", 12th USA/Europe Air Traffic Management R&D Seminar, Seattle, June 2017.

The analysis methodology was published in a complementary conference paper *"A decision support tool for strategic conflict management through assignment of calculated take-off times"* that was presented at the *International Conference on Harbour, Maritime & Multimodal Logistics M&S – HMS, 2017* and also, a description of this methodology can be found in the paper *"STAM-based methodology to prevent concurrence events in a Multi-Airport System (MAS)", Transportation Research C* ***(under review)****.*

Chapter 4

4. Application and experimental results

A STAM-based methodology to reduce the number of ATC interventions on air has been developed during this research study. The three-step methodology, composed by detection, analysis and mitigation, was used to develop a framework designed to be executed as a recurrent TBO service. The spatio-temporal interdependency analysis method provides a baseline to design new metrics that could support the application of alternative pre-tactical measures to the current MDI.

The three different models have been with quite promising results. The methodology of the *detection tool* has been improved including an efficient 3D mapping process, a spatio-temporal interdependency detection and an intelligent neighbourhood search. The development of the tool can be seen during the research process. The tool has been validated within the scope of the AGENT and PARTAKE project and can process one day of traffic in less than 50 min. in a standard desktop computer. Furthermore, the detection of 2h of traffic takes only a few minutes.

The *analysis tool* is an innovative approach to identify topologies among interdependencies detected with the detection module and that cannot be removed by the CTOT (constrained) shifting. Furthermore, this process is useful to name the trajectories that should be removed at the mitigation phase in order to provide a more robust departure coordination solution. The analysis tool translates pairwise potential concurrent events described by using 4 dimensional coordinates into a planar representation allowing its visualization. This simplification is a useful tool to graphically analyses the whole system, since the information encoded in the mapping output list is presented as an interdependence graph. Finally, induced metrics such as the concurrence and coupling level can be extracted from the intrinsic information encoded in the graph representation and used later by the mitigation tool. The concurrence interdependencies will be a function of the number of aircraft occupying a particular cell, in other words, this level will be the size of the potential conflict encoded by the node. The coupling level of one aircraft, which will be used as a weight in the objective function of the constraint programming model for the resolution phase, will be a function of the degree of the nodes where it passes and its path length.

The mitigation tool has been one of the main working areas during this research. A Constraint Programming model was developed for solving the concurrence events that might occur when the departure traffic is inserted into the en-route traffic. The model has been evolved during the research leading from a single CTOT shift to a version that represents the whole trajectory using the concept of segments. As an initial step, the simple model has been tested over a realistic scenario showing the occupation of the cells before and after the mitigation process. Then, an experiment was carried out in which the method of reification was added to the model to identify saturation levels.

During the research period the mitigation model has been further extended. Now, the Constraint Programming model is considering different flight levels, slight speed adjustments and time uncertainty.

Finally, the methodology has been tested as a unit. In order to reduce the look-ahead time, the tool was tested in a Terminal Manoeuvring Area (TMA). In particular, the London Terminal Manoeuvring area. The results of various fast simulations of a realistic scenario are summarized in an article that has been submitted to the Journal Transportation Research Part C.

4.1. Relationship to papers

The proposed methodology has been tested using different realistic and traffic scenarios and fast simulations. The paper

N. Schefers, J.J. Ramos: "A case of a modelled saturation level for cooperative flight departures". Int. J. Simulation and Process Modelling, Vol. 13, No. 4, 2018, p. 310-323.

Shows the application of the model to an over-stressed realistic scenario. The scenario was composed of a set of 4010 real 4D trajectories in the European airspace for a time window of 2 h. In this work, TBO without uncertainties was assumed. The main focus of this paper was to prove the right way of working of the tool. Taking an extract of the paper it can be seen in Figure 12 and Figure 13 the traffic through the cells with potential concurrence events and the conflict free solution.

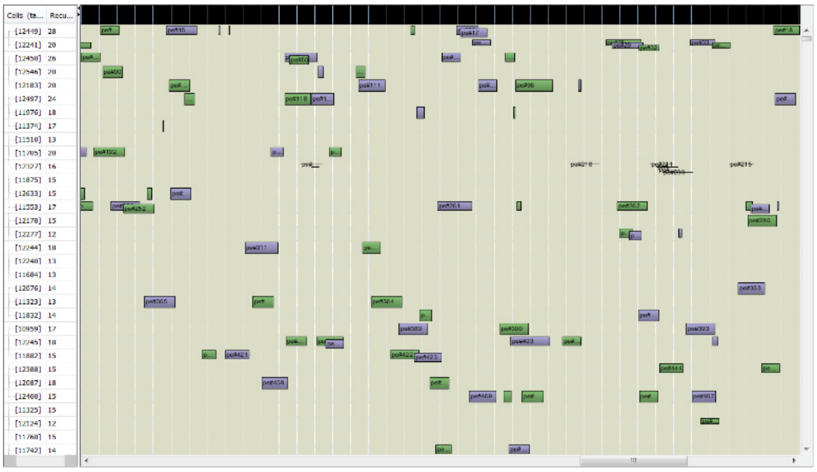


Figure 12: Gantt diagrams showing the traffic through the cells with potential concurrence events, the dagram shows the emerging conflict after inserting the departing traffic for the same time period.

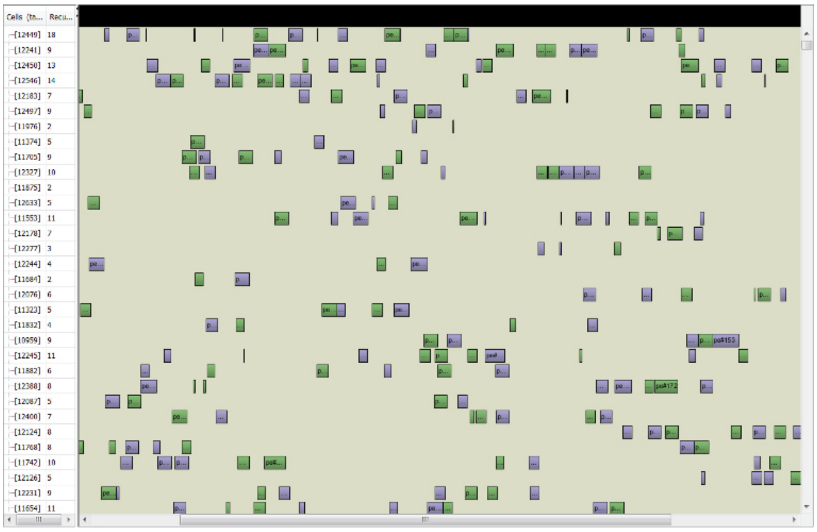


Figure 13: The diagram shows the conflict free solution after applying small adjustments on CTOT and segment' speed.

Furthermore, in the articles:

J.J. Ramos, N. Schefers, M. Radanovic, M.A Piera, P. Folch: "A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures", 12th USA/Europe Air Traffic Management R&D Seminar, Seattle, June 2017.

N.Schefers, J.J. Ramos, P.Folch, J.L Muñoz: "A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures", Transportation Research C.

In the latter, the model was applied to a 1h traffic scenario covering the BeNeLux airspace to show the effect of the tool under time uncertainty. Under the assumptions expressed in the paper, the effects on the time diversion on the conflict window can be seen in Figure 14. For this experiment, a headwind of 50 knots or 92.6 km/h at FL 360 was assumed (ATSC113 2017). The total time needed to recover the time diversion in this case is 10.6 minutes (636 seconds).

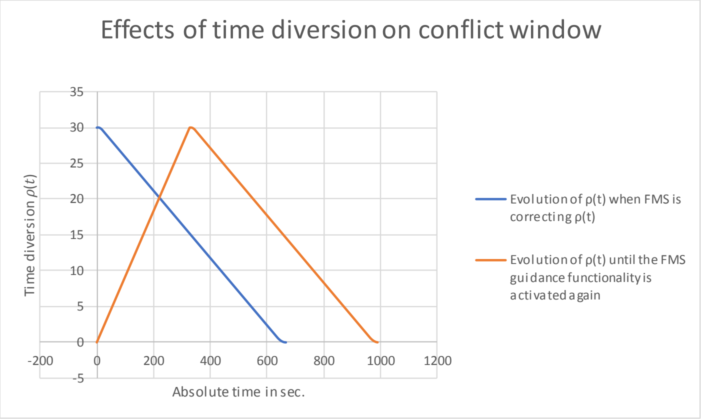


Figure 14: Effects of time diversion $\rho(t)$ on conflict window of the experiment

Finally, the proposed methodology has been adjusted to the environment of a Terminal Maneuvring Aera. The results are documented in the paper

N. Schefers, M.A. Amaro, J.J. Ramos, F. Saez: "STAM-based methodology to prevent concurrence events in a Multi-Airport System (MAS)", Transportation Research C ***(under review)****.*

As an initial step, a traffic scenario was selected to perform the fast simulation and to provide recommendations about the most relevant operating parameters: cell size, number of operating airports and look-ahead time. It was used a sample traffic data of 19th of July 2017 from 6am to 7am. LTMA has been the target of an important number of regulations during summer of 2017 (including the 19th of July 2017), and most regulations occurred in the traffic peak period between 6:00am and 7:00am (Eurocontrol 2017). The number of concurrence events that were detected can be seen in Figure 15.

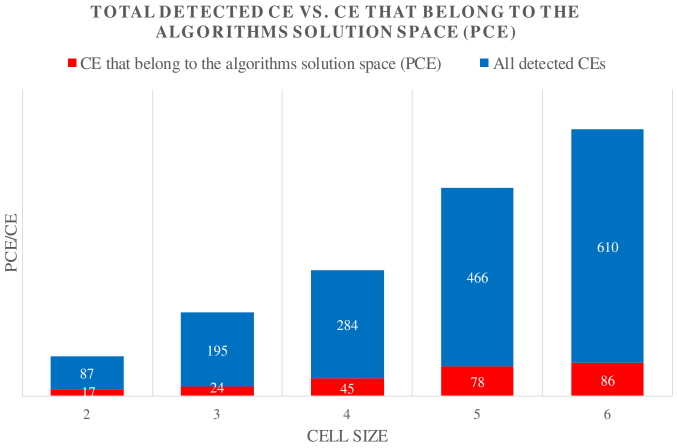


Figure 15: Total detected CE and PCEs according to the applied cell size

Further experiences have been perfromed using different traffic scenarios to evaluate the optimal working parameter for the tool in terms of : cell size, number of operating airports and look-ahead time.

Chapter 5

5. Paper 1

In addition to the literature review given above, the first paper “Causal analysis of airline trajectory preferences to improve airspace capacity” that has been published in Procedia Computer Science 104, p. 321-328, narrows the topic within the ATM framework by illustrating ATM concepts such as ATM planning layers, the TBO concept and the 4-D trajectory management. The paper analyses the existing system, the description of a new vision for the short term demand capacity balancing, and establishes the basic elements for the operational environment.

Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 104 (2017) 321 – 328

Procedia
Computer Science

ICTE 2016, December 2016, Riga, Latvia

Causal Analysis of Airline Trajectory Preferences to Improve Airspace Capacity

Nina Schefers[a,*] , Miquel Angel Piera[a] , Juan José Ramos[a] , Jenaro Nosedal[b]

[a]Universitat Autònoma de Barcelona, C/ Emprius 2, 08202 Sabadell, Spain
[b]York University, 4700 Keele St, Toronto, ON M3J 1P3, Canada

---

Abstract

The problem of fitting the maximum number of aircraft into ATC sectors, keeping in mind aircraft separation and safety standards, area navigation direct routings and other factors, is known as the airspace capacity problem. Above the European airspace, a high density network of air traffic can be found which is determined by the workload of controllers. Constraint Programming (CP) is a powerful powerful paradigm for representing and solving a wide range of combinatorial problems. The PARTAKE project fosters adherence of air space user's trajectory preferences enhancing Trajectory Based Operations (TBO) concepts by identifying tight interdependencies between trajectories and introducing a new mechanism to improve aircraft separation at the hot spots by the mean of CP. The underlying philosophy is to capitalize present freedom degrees between layered ATM planning tools, when sequencing departures at airports by considering the benefits of small time stamp changes in the assigned slot departures.

Keywords: Air traffic management; Trajectory Based Operations; Decision Support Tool; Airspace capacity

---

1. Introduction

As widely known, air transport industry plays a major role in world economic activity and remains one of the fastest growing sectors of the world economy. Because of the continued growth in civil aviation, in many places,

---

* Corresponding author. Tel.: +34 633456617.
E-mail address: ninarebecca.schefers@uab.cat

doi:10.1016/j.procs.2017.01.141

demand often exceeds the available capacity of the air transport system to accommodate air traffic, resulting in significant downstream effects[1].

The processes used in the International Civil Aviation Organization (ICAO), such as the Flight Plan, have proved their efficiency, however it is well accepted that there are several shortcomings regarding their performance.

According to the ICAO (Doc. 9854), it was already recognized in the 1980s that the existing approach to the provision of Air Traffic Services (ATS) and the air navigation system was limiting continued aviation growth and constraining improvements in safety, efficiency and regularity. However, it became clear that the changes needed to improve the operational concept cannot be achieved by revolution but have to undergo an evolutionary process.

The ICAO ATM operational concepts are applied in several integrated service areas. To better understand the complex interrelationships a short description is summarized. In this research, the ATM System is understood as a holistic entity consisting of seven ATM conceptual components[1]:

- Airspace organization and management
- Demand/capacity balancing
- Aerodrome operations
- Traffic synchronization
- Conflict management
- Airspace user operations
- ATM service delivery management

In order to have a well-functioning ATM system, all these components have to be present and properly integrated. In addition to the seven concept components, the exchange and management of information used by the different processes and services is of great importance.

Furthermore, the airspace organization and management provides the strategies, rules and procedures by which the airspace will be structured to accommodate the different types of air activity, volume of traffic, and different levels of service and rules of conduct. These management activities are underlined by the demand and capacity balancing that can be divided into strategic-, pre-tactical-, and tactical stages[1].

In Europe, an Air Traffic Flow Management (ATFM) service has been established to use the given capacity to the maximum extent possible keeping in mind the guiding principles safety, continuity and expeditious for the flow of air traffic. On strategic level, demand and capacity balancing will respond to the fluctuations in schedules and demands using the Integrated Initial Flight Plan Service (IFPS) where Airspace Operators (AO) and Air Traffic Service Units (ATSU) can specify their most economic and efficient flight plan or repetitive flight plan. All activities are based on principles of the Air Traffic Flow and Capacity Management (ATFCM) and regional European supplementary procedures described in the ICAO document 7030. Information can be retrieved from the System Wide Information Management (SWIM) platform, an advanced technology program designed to facilitate greater sharing of ATM system information, such as airport operational status, weather information, flight data, status of special use airspace, and National Airspace System (NAS) restrictions. At this stage, planning activities are fulfilled with a timeframe of seven or more days before the operation day.

At pre-tactical and tactical stage demand and capacity balancing evaluates the current allocation of the ATM service provider, airspace user and aerodrome operator assets and resources against the projected demands applied approximately 6 days to 1 day before the operation day. Approaching the operation day, demand and capacity balancing focuses more detailed on demand management to adjust imbalances where activities take place between 5 days and 3 hours prior to departure. The system involved at this stage is the Enhanced Tactical Flow Management System (ETFMS) that receives metadata from the IFPS by Air Traffic Service (ATS) Data Exchange Presentation format and based on this input tracks the aircraft with accurate near-to-real-time data, recalculating 4D profiles of flights allowing traffic demand to be understood more precisely. Integrated in the ETFMS is the Computer Assisted Slot Allocation (CASA) system that operates under the “First-Planned, First-Serve” policy. The CASA system calculates the Estimated Time Over for each point of entry in each sector and allocates the Estimated Off-Block Time (EOBT) plus the taxi-time at the departure aerodrome and finally provides the Calculated-Take-Off-Time (CTOT) that must be followed within a -5 to +10 minutes’ slot window[2].

At operational level, the strategic ATFCM concept is taken over by the Air Navigation Service Provider (ANSP) using Air Traffic Control (ATC) systems as for instance the Flight Data Processing System (FDPS) that is based on a trajectory-based model and which is interconnected with external sources (e.g. Network Manager) to exchange data.

Attempting to improve the slot situation, new information processes and systems are under development to meet the current European capacity demands. The goal hereby is to improve the flight planning process and the supporting systems to create shorter routes, reduce emissions, reduce delays and improve the connectivity of trajectories. As a result, the ATFCM adherence measured at its effect and safety level can be revealed and the overload of ATC workload in dense sectors could be decreased.

The paper is organized as follows: Section 2 explains the PARTAKE Project, section 3 describes the tight trajectory detection, and section 4 outlines the tight trajectory resolution. Solutions obtained and an outlook for future research will be given in section 5 and 6.

2. The PARTAKE project

The approach presented in this paper follows the research project PARTAKE[3]. It is a Research Exploratory H2020 project that aims to help mature new concepts for ATM emerging technologies and methods proposing new approaches to improve airspace capacity. The seeks to improve the present demand/capacity balance in ATM by introducing small ground delays in the programmed departure that will not affect the planned traffic since the slot time window assigned to each aircraft will be preserved. The mayor challenge PARTAKE is facing is to reach a robust combination of Reference Business Trajectory (RBT) time stamps.

The vision of the PARTAKE project is to enable a flexible synchronization mechanism that will support an efficient and competitive use of the ATM services based on an intelligent cooperative combination of the time stamp component of the RBT agreed by the Airspace Users (AU's). The core research activities in PARTAKE are geared toward the next 4 concepts:

2.1. Tight trajectory interdependencies: Mitigating adherence problems

In PARTAKE[4], 4-dimensional trajectories (4DT) are considered as a precise description of an aircraft path in space and time which include the "centerline" of the path, using Waypoints (WPs) to represent specific steps along the path, together with appropriate buffers to describe the associated position uncertainty. The path contains altitude descriptions for each WPs and suitable indications about the time(s) at which the trajectory will be executed. Some of the WPs in a 4DT path may be associated with Controlled Time of Arrivals (CTAs). Each CTA is defined by a Target Time of Arrivals (TTAs) requirement that must be met by the aircraft within a specified time tolerance. Therefore, CTAs actually represent time "windows" for the aircraft to cross specific waypoints and will be used to improve the clearance between aircraft at identified concurrence events.

2.2. Gap Analysis of time stamp combinations to improve time clearances

A causal model is used to analyse the RBT's interdependencies quantified by the temporal looseness. Tight interdependencies (i.e. loose of separation minima) can be relaxed by a small adjustment of the CTOTs of the involved aircraft preserving the TTA and the slot assigned at strategic level. In this way, the "first planned, first served" policy used by most airports could be improved since this policy is justified only due to a lack of tools and relevant information that could analyse the downstream impact of different sequencing departures on saturated sectors.

2.3. Improving adherence robustness through relaxing some non-relevant time stamp contracts

Tight interdependencies enhances the propagation of perturbations, thus, the effects of a poor time waypoint adherence in a high density sector can generate a huge amount of changes in the rest of the trajectories, whereas poor time waypoint adherence in those sectors without tight interdependencies do not create side effects. There are few sectors in Europe with tight interdependencies, which allow adjusting waypoint time-stamps in those areas with a low occupancy factor and negligible soft interdependencies. Thus to preserve time stamp agreements at tight waypoints, it is possible to relax time stamps in some areas to compensate the effect of potential uncertainties (departure time uncertainty and cruise speed uncertainty) or to extend the functionality provided by calculating the CTOT.

2.4. Dynamic, multi-objective optimization model to support AU's business targets

ATM metrics such as Traffic Density, Peak Load, Occupancy and Number of Conflicts will be evaluated in each sector based on the AU's trajectories and the PARTAKE trajectories to synthesize performance comparative indicators at micro level, so the different stakeholders will be able to check the benefits of the developed tools.

In PARTAKE, pre-flight RBT's (at departure) and en-route RBT's (network scope) are mapped into micro-regions pre-flight (trajectory scope) to identify interdependencies and compute feasible clearances to relax tight interdependencies while preserving ATFM TTA and departure slot time constraints. The model to identify the tight trajectory interdependencies will be specified in Coloured Petri Net formalism for an efficient causal analysis while the time stamp control will be evaluated in Constrain Programming (CP). A Service-Based Architecture (SOA) will be used to implement the interface with SWIM while agent-based technologies will be deployed to evaluate in a simulation environment the acceptability of the solutions by the AU's.

3. Tight trajectory interdependencies detection

PARTAKE methodology considers three steps to detect tight concurrence events before the take-off times are slightly adjusted by CP. The first process is the Macro-mapping process, followed by the second process the Micro-mapping process. The third process is based on a Filtering process. Once the tight concurrence events have been detected, slight adjustments on the takeoff time based on CP solutions are applied.

The macro and micro detection process are based on the traffic mapping onto a grid of square macro-cells (12 NM). The grid spans over European Civil Aviation Conference (ECAC) airspace in its totality. The input trajectories (RBT) must be discretized in time-equidistant samples. Each sample contains the horizontal position, indicated by geographical coordinates, and altitude. The position in the sequence of discrete points represent the relative time instant with respect to the known CTOT. The time stamp of each trajectory point can therefore be calculated from the sequence according to the sampling period.

All trajectories are loaded and mapped onto the grids of square macro-cells. Entry and exit times are registered in order to get the cell occupancy time window. Detection at macro-cell level is implemented by determining those macro-cells where more than one aircraft has been detected, indicating the presence of regions that may contain concurrence events. Next step is micro mapping: each macro-cell with potential concurrence events is divided into four microcells, with quadrants named I, II, III and IV. The partition procedure is shown in Fig. 1a, where C_{i1} refers to quadrant I of cell C_i etc.

To determine whether a trajectory occupies one of the four microcells (squares of 6 NM), the trajectory points within the macro-cell are analysed and the occupancy time window $[t^a_{entry}, t^a_{exit}]$ is registered. Detection at micro-cell level is implemented by determining those micro-cells where more than one aircraft has been detected. The detection process cannot be limited to one (macro or micro) cell occupancy analysis. The potential concurrence events with trajectories at the surrounding cell must be also investigated. Fig. 1b illustrates this shifting analysis. All the potential conflicts are registered providing position information about the quadrant and the cell of the overlapping of two or more aircraft and the aircraft involved in the overlap. This set of potential concurrence events is the input for the next filtering module.

The filtering process to be implemented in this module shall filter those trajectories either losing the required clearance (separation minima) or in a risk of losing it after mitigation measures are applied. The filtering process is based on the collective micro-regions detected in the mapping tool. For these collective micro-regions, entry and exit times are used to determine the temporal looseness, referring to the size of the overlap or clearance between aircraft pairs.

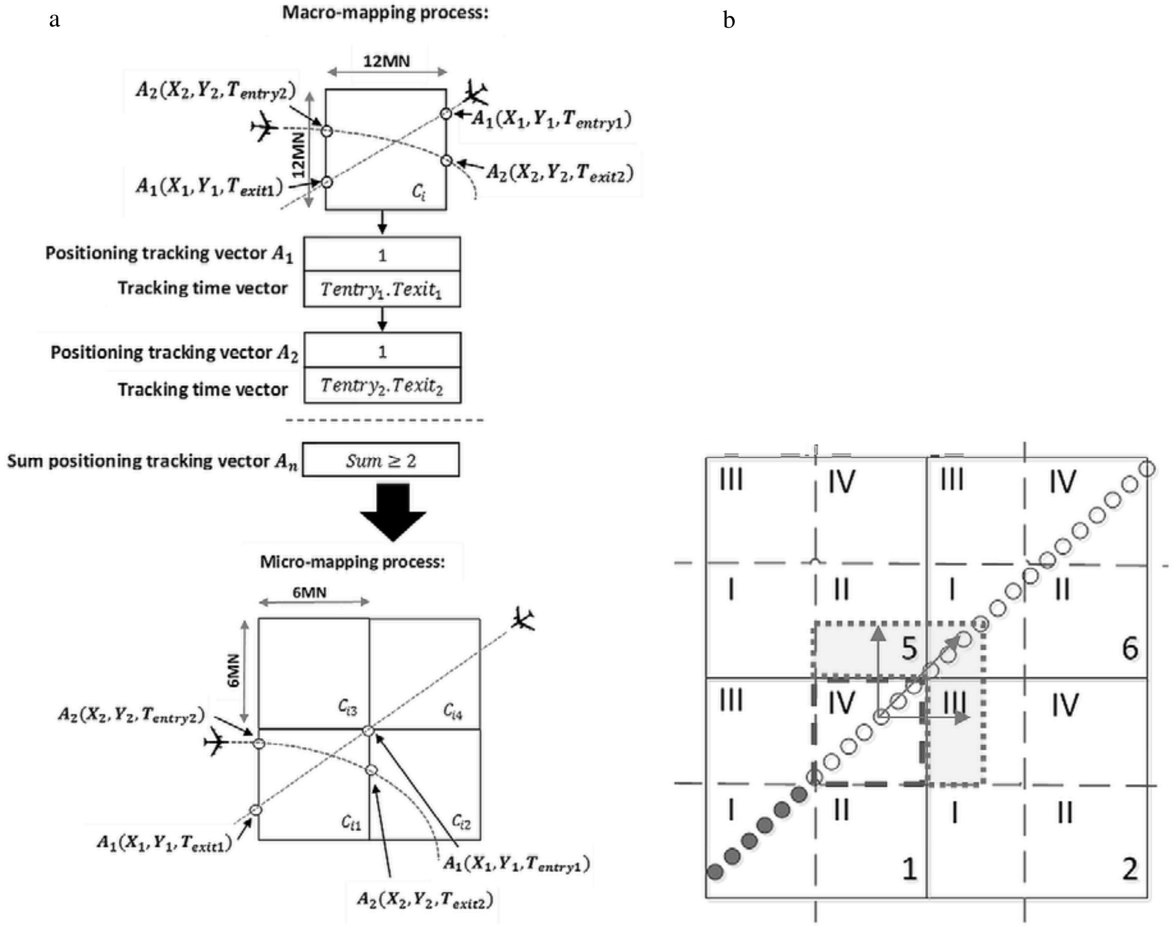


Fig. 1. (a) Micro and macro mapping processes; (b) Neighbourhood detection.

The calculation of the temporal looseness H between time windows of aircrafts $a_1$and a_2 in a collective micro-region is expressed as follows:

$$H = \min\left(t_{exit}^{a_1}, t_{exit}^{a_2}\right) - \max(t_{entry}^{a_1}, t_{entry}^{a_2})$$

Concurrence events exist when H is positive, indicating an overlap, whereas events with a negative H value have a clearance time, indicating a potential concurrence event. Based on the calculation of H (the size of an overlap or clearance), it is possible to identify the ‘‘tightest’’ concurrence events, or potentially concurrence events, for each pair of aircraft. Hence, to shorten the overall list, all redundant or highly slack events between pairs of aircraft are eliminated, whereas the most critical or closed interactions are retained. Because departure slot allocation times must be respected, the maximum value for a time adjustment on CTOTs will be considered to be between -300 s and $+600$ s. Therefore, potential concurrence events with a clearance time longer than 600 s have sufficient time separation to be neglected, even when the maximum adjustment time is applied. A safety buffer S can be added to the 600 s in order to ensure a clearance time S between any pair of aircrafts going into a collective micro-region.

4. Tight trajectory interdependencies resolution

The mitigation tool aims at finding the proper mitigation actions for elimination the detected tight interdependencies. In PARTAKE, trajectories that show a tight interdependency should be resolved by applying a CTOT shifting of +5 and -10 minutes and slight speed adjustments since the TTA need to be preserved as much as possible (see Fig. 2). Because of the strong complexity associated with solving time adjustment allocation problems and to find solutions within a reasonable computational time, the fine-tuning process is implemented as a Constraint Programming (CP) model, expressed in terms of three main entities: decision variables, their corresponding domains, and constraints relating them.

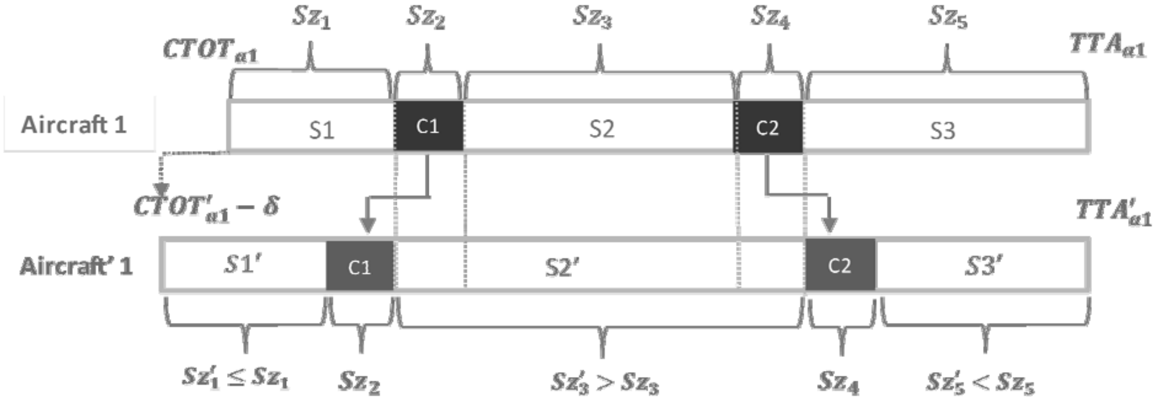


Fig. 2. Modifications on the A/C RBT by CTOT Shifting and Speed adjustments actions.

In PARTAKE, TTA adherence is a main objective to enhance capacity at arrival airports. Clearly, the TTA cannot be preserved by shifting the CTOT and therefore, the full trajectory. Therefore, speed adjustment should be introduced in the A/C trajectory. To meet TTA conditions, the trajectory is divided into segments. The Fig. 2 illustrates this concept. For instance, aircraft 1 in the figure is divided into five segments: C_1 and C_2 represent the concurrence events while S_1, S_2 and S_3 are the segments between the concurrence events. In the modified trajectory, the segment S'_1 is shifted according to the applied delay on the CTOT to avoid the first concurrence event while S'_3 is shortened in time by speed change in order to preserve the TTA within the margin. The intermediate segment S'_2 is extended in time by flying with reduced speed to avoid concurrence event C_2.

The mitigation algorithm shall be formulated as an optimization problem where the constraints are formulated to remove the tight interdependencies. The mitigation tool is based on the following modelling structures (see Table 1).

Table 1. Mitigation algorithm modelling structures.

Data structure	Explanations
A set of aircrafts	
C set of cells at a collective microregion	
$C_A = \{< c, a > \mid \forall c \in C, \forall a \in A\}$	$c_a =< c, a >$ the pairing between the aircraft a using a given cell c at the microregions.
$RBT_a = \{\hat{g}_i^a \mid \forall a \in A,\ i = 1..p(a)\}$	$\hat{g}_i^a$ is a segment of the aircraft a trajectory and p is the number of segments required for describing the trajectory
Decision variables:	
d.v. $\delta_a \in [-\delta_{min}, \delta_{max}], \forall a \in A$	To ensure that the departure adjustment of the aircraft remain in the defined timeframe of [-5,10] minutes
d.v. $P_{c_a} \in [c_a^{te} - \delta_{min}, c_a^{ts} + \delta_{max}], \forall c_a \in C_a$	Interval for the occupancy of the cell c by an aircraft a with its’

d.v. $F_c = \{P_{c_a} | c_a \in C_A\},\ \forall c \in C$

d.v. $G_a,\ \forall a \in A$

d.v. $g_i^a,\ \forall a \in A,\ \forall i \in 1..p(a)$:

$sz(g_i^a) \in [sz(\hat{g}_i^a) - l(\hat{g}_i^a), sz(\hat{g}_i^a) + l(\hat{g}_i^a)]$

d.v. $T_a = \{g_i^a\}, \forall a \in A$

Objective function and constraints:
minimize

$$w_1 \sum_{a=1}^{n} |\delta_a| + w_2 \sum_{a=1}^{n} L(G_a)$$

subject to {

$s(g_i^a) = CTOT_a \pm \delta_a\ \forall a \in A$

$\forall P_{c_i}, P_{c_j} \in F_c$

$NO(F_c) \Leftrightarrow\ \pi(P_{c_i}) < \pi(P_{c_j}) \Rightarrow e(P_{c_i}) \le s(P_{c_j})$

$span(G_a, \{g_i^a\}), \forall a \in A, \forall g_i^a \in T_a$

$\forall a \in A,\ \ \forall i, j \in 1..p(a)$

$NO(G_a) \Leftrightarrow \pi(g_i^a) < \pi(g_j^a) \Rightarrow e(g_i^a) \le s(g_j^a)$

$e(g_i^a) \le s\left(g_j^a\right) :\ i \le j$

$e(g_i^a) = s\left(g_j^a\right) : j = i + 1$

$$\begin{cases} s(g_i^a) = s(P_{c_a}) \\ e(g_i^a) = e(P_{c_a}) \end{cases} \Leftrightarrow \begin{matrix} {\scriptstyle s(\hat{g}_i^a) = c_a^{te}} \\ {\scriptstyle e(\hat{g}_i^a) = c_a^{ts}} \end{matrix}, \forall c_a \in c_A$$

size and start and end time
Each of the cells can be occupied by one aircraft at a time, so the aircrafts going through the cell must be sequenced accordingly.
Representation of the entire flight trajectory where s_a will be the take-off time and e_a the arrival time in the solution.
Interval variables representing the segments of the G_a and their size.

Sequence variable T_a is introduced to set the relationship between the trajectory segments g_i^a and the entire trajectory G_a:

It might happen that no solution is found because time adjustment is bounded so it is possible that the required delays δ_a cannot be compensated by the speed adjustments. For this reason, the TTA constraint is relaxed. The number of TTA violations can be counted for introducing its minimization as an objective together with the objective function to minimize the total delay of the aircraft takeoffs.

The duration of the flight is determined by the constraint of the take-off time and the time to arrival
No overlap is guaranteed for the concurrence event P_{c_i} at a position prior to any P_{c_j} by constraining its exit time to be lower or equal to the entry time of the subsequent proximate events
The *no overlap* constraint that imposes a set of interval variables to not overlap each other in time
The constraint *span* states that the interval flight spans over all present intervals from the set segments.

Interval variables do not overlap each other
One segment has to start before the next
start of segment *j* results after the end of segment *i*
The P_{c_a} interval variable, that is used in combination with the sequence variable F_c to remove the concurrence events at cell c, must be linked with the concurrence segments of the trajectory T_a

5. Results obtained for trajectory adjustments

The data that was used for this experiment was obtained from an over-stressed scenario with the duration of 2 hours that is composed of 4010 4D trajectories flying above the European airspace. The trajectories were discretized every second giving information about longitude, latitude, altitude and speed and TBO were assumed to be without uncertainty. Originally, this scenario was designed and analyzed in the STREAM project and EUROCONTROL SESAR WP-E project.

Before introducing slight departure time adjustments, conflicts can be clearly seen in the Gantt. After executing the presented algorithm for mitigating trajectories with potential concurrence events, all conflicts could be removed by applying delays on the CTOT and/or adding speed adjustments with less than 10% modification of the RBT proposed originally by the airline. The ILOG CP solver was limited to 180 seconds to get the best suboptimal solution. All the experiments were performed on a Window 10 computer with an Intel Core I7 CPU 2,30 GHz and 16GB RAM.

Acknowledgements

This research is supported by the European Union's Horizon 2020 research and innovation program. The Project related to this research is PARTAKE "Cooperative departures for a competitive ATM network service" with Grant Agreement No. 699307. Opinions expressed in this paper reflect author's views only.

References

1. ICAO. Global Air Traffic Management Operational Concept. Doc. 9854. AN/458. First Edition; 2005.
2. Cook A. European Air Traffic Management – Principles, Practice and Research; 2007.
3. PARTAKE. Project Proposal; 2015.
4. PARTAKE. Deliverable 1.1 - Report on PARTAKE functional and non-functional requirements; 2016.

Nina Schefers received her bachelor degree in International Information management from the Universität Hildesheim, Germany in 2013 and her master degree in Logistics and Supply Chain Management from the Universitat Autonoma de Barcelona (UAB), Spain in 2015. Currently, she is a Ph.D candidate at UAB with research work related to aeronautics and logistics. Her research line is related to decision making and optimization of processes in Logistics, Manufacturing and Transportation.

Juan J. Ramos is a researcher focusing on modelling, simulation and optimization of dynamic systems, especially in the field of logistics. He received his Ph.D. from the Universitat Autonoma de Barcelona (UAB), Spain in 2003, where he is professor at the Dep. of Telecommunication and System Engineering. He is currently the program Director of the European Master on Logistics and Supply Chain Management at UAB. He is a member of LogiSim, a recognized research group on Modeling and Simulation of Complex Systems. Furthermore, he is expert in production technologies/logistics, intelligent transport systems, information and communication technology, industrial collaboration and technology transfer.

Jenaro Nosedal-Sánchez received his bachelor and master degree in Industrial Engineering from National Autonomous University of Mexico (UNAM) and Ph.D. from Universitat Autonoma de Barcelona, Spain. As Deputy Director of High Impact Projects at Mexico's National Council of Science and Technology was responsible of funding management for R&D project related to Aeronautics and Airport Management. Currently, he is postdoctoral fellow at York University, Canada. His research line is modeling and simulation for process improvement in Management, Logistics, Manufacturing and Transport Systems.

Miquel Angel Piera Eroles is associate Professor in the System Engineering Department at Universitat Autònoma de Barcelona. Miquel graduated with excellence from UAB in Computer Engineering (1988), Msc from University of Manchester Institute of Science and Technology in Control Engineering (1991), and PhD from UAB in 1993. Dr. Piera is former deputy director of the UAB Engineering School and director of LogiSim (research group on Modelling and Simulation of Complex Systems). Dr. Piera has received several awards and recognitions, among which it is mentioned the "Outstanding Professional Contribution Award" from the internal Society for Computer Simulation (SCS) in USA in 2013. He has coordinated as Scientific Coordinator more than 10 Spanish research projects and more than 20 Industrial funded projects, he has also participated in a number of EC funded research and academic. He is author of more than 100 scientific papers, 9 scientific books and has been invited as Key note speaker in more than 10 international conferences.

Chapter 6

6. Paper 2

The paper "A case of a modelled saturation level for cooperative flight departures" that has been published in the International Journal of Simulation and Process Modelling, Vol. 13, No. 4, 2018, p. 310-323 shows the methodology of the detection tool and a detailed description of the development of the mitigation tool using Constraint Programming formalism. In this work, a CP model is presented for solving the concurrence events that might occur when the departure traffic is inserted into the en-route traffic. It can be seen that the complexity of the proposed model increases from a simple shift of the trajectory towards introducing the concept of segments which make it possible to describe the whole trajectory from departure until the arrival time to the destination. Finally, in this paper, the concept of reification was introduced to the model to detect potential saturation levels of conflict scenarios. Compared to other models, this research is based on the partitioning of the sky into cells that are used to detect concurrence events and mark the design of the here presented CP mitigation tool. The model has been proved in a realistic and overstressed scenario and it has been able to find suboptimal solutions in a timeframe of 180 seconds for all the performed experiments.

A case of a modelled saturation level for cooperative flight departures

Nina Schefers* and Juan José Ramos González

Technical Innovation Cluster on Aeronautical Management,
Universitat Autònoma de Barcelona, Spain
Email: NinaRebecca.Schefers@uab.cat
Email: JuanJose.Ramos@uab.cat
*Corresponding author

Jenaro Nosedal

Faculty of Liberal Arts & Professional Studies,
School of Administrative Studies,
York University, Canada
Email: jnosedal@yorku.ca

Abstract: Owing to increasing air traffic operations, the development of advanced decision support tools (DSTs) in air traffic management (ATM) is driven forward to guarantee that sustainable transport logistics balance airspace capacity with user demands. In this paper, the tuning of calculated-take-off times (CTOTs) as a tool for mitigating the propagation of perturbations between trajectories in dense sectors is analysed. The proposed methodology uses a powerful tool for predicting potential spatio-temporal concurrence events between trajectories over the European airspace. In the first place, the aim is to remove the detected concurrence events by considering bounded time stamp adjustments on strategic agreed points of the aircraft trajectory. In the second place, the model is extended to identify route interdependencies of over constraint topologies that could lead to a saturation event. The approach is based on a robust constraint programming model aiming to determine the feasible time stamp changes considering reference based trajectories (RBTs).

Keywords: air transportation; constraint programming; air traffic management; decision support tools; airspace capacity; trajectory based operations; air traffic control; air traffic flow management; conflict detection; scheduling; reference based trajectory; calculated take-off time; reification.

Reference to this paper should be made as follows: Schefers, N., González, J.J.R. and Nosedal, J. (2018) 'A case of a modelled saturation level for cooperative flight departures', *Int. J. Simulation and Process Modelling*, Vol. 13, No. 4, pp.310–323.

Biographical notes: Nina Schefers received her Bachelor in International Information Management from the Universität Hildesheim, Germany in 2013 and her Master in Logistics and Supply Chain Management from the Universitat Autonoma de Barcelona (UAB), Spain in 2015. Currently, she is a PhD candidate at UAB with research work related to aeronautics and logistics. Her research subject is related to decision making and optimisation of processes in logistics, manufacturing and transportation.

Juan José Ramos González is a researcher focusing on modelling, simulation and optimisation of dynamic systems, especially in the field of logistics. He received his PhD from the Universitat Autonoma de Barcelona (UAB), Spain in 2003, where he is a Professor at the Dept. of Telecommunication and System Engineering. He is currently the Program Director of the European Master on Logistics and Supply Chain Management at UAB. He is a member of LogiSim, a recognised research group on modelling and simulation of complex systems. Furthermore, he is an expert in production technologies/logistics, intelligent transport systems, information and communication technology, industrial collaboration and technology transfer. He is a co-founder of Aslogic S.L.

Jenaro Nosedal-Sánchez received his Bachelor and Master in Industrial Engineering from National Autonomous University of Mexico (UNAM) and PhD from Universitat Autonoma de Barcelona, Spain. As Deputy Director of High Impact Projects at Mexico's National Council of Science and Technology, he was responsible for funding management for R&D projects related to aeronautics and airport management. Currently, he is a Postdoctoral Fellow at York University, Canada. His research line is modelling and simulation for process improvement in management, logistics, manufacturing and transport systems.

This paper is a revised and expanded version of a paper entitled 'An efficient constraint programming model for cooperative flight departures' presented at HMS2016 in Larnaca, Cyprus, 26–28 September.

1 Introduction

As stated in the European ATM Master Plan, aviation is an important driver of economic growth predicted to have steady growth in the next decades. Therefore, the expansion of the air traffic management (ATM) system towards a performance-driven and technologically enhanced architecture is inevitable to acquire greater connectivity and to ensure the sustainability of the aviation sector in Europe as stated in Sesar (2015). The intention of the here presented innovative approach is to enhance the design of a competitive ATM system by supporting up to a certain extent the Airspace User (AU) demands at the right time (i.e., departure slots), at the right cost (i.e., suitable level of Air Traffic Control (ATC) service) at the right place (i.e., AU's preferred trajectories) and at the right service quality (i.e., safety). This is achieved without extra investments, just by removing the ATM non-added-value operations (e.g. control, storage or transfer, etc. Tajini et al., 2014) which indirectly impacts on present ATM capacity.

By empowering the concept of trajectory-based operations (TBO) as a flexible synchronisation mechanism towards an efficient and competitive ATM service a precise description of an aircraft path in space and time can be retrieved. Under the TBO approach, airspace users should fly precise 4-dimensional trajectories (4DTs), previously agreed upon with the network manager (SKYbrary, 2017).

Europe has some of the busiest airspace in the world, compiled from 44 member states united in the European Civil Aviation Conference (ECAC) region. The Network Manager Operations Centre receives, processes and distributes up to 35,000 flight plans a day. This concerns over 500 European airports and airfields as described in (Eurocontrol, 2017). To safely operate this demand any AU that intents to depart from, arrive at or overfly one of the ECAC member states must submit a flight plan that must be approved in advance. Once the flight plan has been approved, the Reference Business Trajectory (RBT) is agreed and the aircraft is authorised to proceed in accordance with the RBT consisting of predefined conflict free segments (Cook, 2007).

The ATM network is designed to be robust and resilient to a whole range of disturbances, however, due to its dynamic and complexity, unforeseen disruption can occur at any time and influence its functionality. Delay causes can be found for example in the rotation of aircraft, in the turnaround processes, in Air Traffic Flow Management (ATFM) and Air Traffic Control (ATC) restrictions, in maintenance problems and weather conditions. When the delays exceed the agreed green delay of [–5, 10] minutes, the aircraft must be rescheduled as stated in Nosedal et al. (2014) and Barnier and Allignol (2009).

1.1 State of the art

The development of DSTs to mitigate perturbations between trajectories in a dense airspace has be a relevant topic for research projects and academic studies over the last years, due to the envisioned demand growth researchers from all over the world are working in the field of ATM to enable safety and efficient operations under a more flexible and competitive context. Studies have been made to understand the benefits that the TBO concept provides for strategic deconfliction. For example, the introduction of collaborative decision making (CDM) mechanisms to improve airport and airspace capacity and efficiency.

On the latest USA/Europe air traffic management research and development seminar (ATM, 2017; Xu and Prats, 2017) presented a strategy to include linear holding (LH) into air traffic flow management (ATFM) initiatives, together with the commonly used ground holding and airborne holding measures with the conclusion that incorporating the LH means that more space and periods in the network can be used to absorb delays. Also, Yan and Xavier (2017) provide some results about the implementation of LH for flights initially subject to ground holding, in the context of TBO. The aim of this combined approach is to neutralise additional delays raised from the lack of coordination between various traffic management initiatives (TMIs) and without incurring extra fuel consumption.

Despite LH techniques, Marcella et al. (2017) studied the real-time optimisation of take-off and landing operations at a busy terminal control area in case of traffic congestion. The approach tries to highlight the current aircraft scheduling practice suffers a lack of intelligent decision support by finding good compromise solutions among the various indicators.

Also, other researchers have been assessing rerouting algorithms to solve air traffic congestion as part of the methodologies to use the TBO concept for concurrence event deconfliction. For example in Adacher et al. (2017), graph theory was used to model the air traffic infrastructures to understand the effects of rerouting to solve congestion.

Other techniques have been used to model conflict resolution scenarios based on the TOB concept relaying on CP formalism. Barnier and Allignol (2012) for example presented a ground holding approach to solve all potential conflicts occurring above a given flight level for a day of traffic in the French airspace. Rather than trying to respect sector capacity constraints, each possibly conflicting situation between any two aircraft was modelled based on the TBO concept. The resulting problem size however was huge and therefore, Nosedal et al. (2014, 2015) introduced new mechanisms to detect concurrence events in a more efficient way using a cell system. Based on these findings, this paper introduces a new CP model, based on an efficient concurrence event detection mechanism, able to mitigate concurrence events over the entire European airspace. Based on the CP proposed, the problem takes the form of a scheduling problem where the solution is provided by proposing small adjustment on the CTOT and also by allowing limited speed changes in order to meet the TTA. The present work proposes an improved model to solve the problem by describing the trajectory as a sequence of time intervals that represent the conflict-free segments and concurrence events segments. The scheduling consists of ensuring no concurrent use of the areas that were in conflict.

2 Problem description

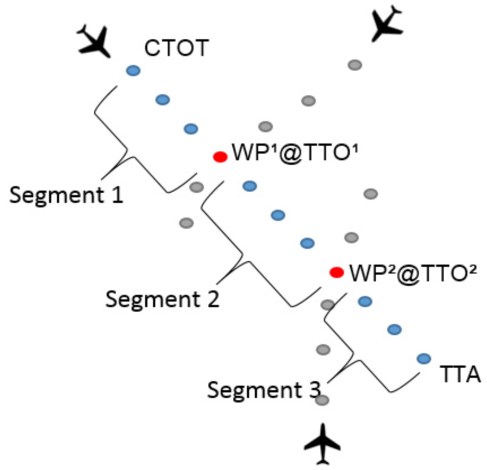
The here presented approach uses as a window of opportunity the agreed green delay time slot of [–5, 10] minutes and reschedules aircraft on the ground in such a way that en-route concurrence events are minimised while the AU preferred RBT is preserved. Small adjustments within the [–5, 10] interval around the calculated take-off time (CTOT), along with bounded modifications on the flight duration, will be considered in the here presented model. The goal of this approach is to significantly reduce the amount of ATC interventions and to maximise adherence of trajectories at key waypoints. Therefore, two kinds of time adjustments are considered in the constraint programming (CP) model:

1 Introduction of ground delays with a time offset of [–5, 10] minutes, remaining in the boundary of green delays to achieve fairness between airlines, since greater delays are quite unpopular as they can be very costly, can cause discomfort among passengers, and affect the strategic airspace configuration.

2 Slight modifications on time stamps for relevant trajectory points. Since a simple shifting of the whole trajectory does not contribute in preserving the target time of arrival (TTA), a more flexible approach is proposed considering additional small time adjustments at strategic points to have a control over the time-to-overfly (TTO) on relevant points close to the hotspot areas.

Using this approach, the goal of reaching the TTA on time as expressed in the ATM concept could be guaranteed by combining the relaxation of the CTOT and the total flight duration as can be seen in Figure 1. The relevant points are identified according to the potential concurrence events that are computed in the detection of tight trajectory interdependencies. Moreover, the TTO stamp of these points is calculated by the conjunction of both the CTOT and the duration of the segments that separate these concurrence events. This approach leads to the resolution of tight interdependencies maximising the trajectory adherence at the waypoints.

Figure 1 Dynamics of CTOT, segments, points with a TTO stamp and a TTA stamp (see online version for colours)



The depicted problem belongs to the class of Constraint Satisfaction Problems (CSP) see Bessiere (2006). During the mapping process, a list of proximate events is detected: Two or more aircraft losing the separation minima. This situation can be represented in terms of constraints able to describe the conditions to be met to avoid such proximate events. For removing these interdependencies, the approach proposes two action mechanisms, that is, two kinds of decision variables for adjusting the relevant time stamps in a way that the constraints modelling the interdependencies are satisfied.

Moreover, this problem can be considered as an optimisation problem, since maximising the adherence of RBTs is set as a goal. Since the decision variables belong to the integer domain, the overall problem falls in the category of combinatorial problems (Huang and Zhao, 2016; Arfi et al., 2016). Finally, for understanding the potential solver incompleteness, the model is tested introducing reification constraints to visualise unsolved concurrence events reaching saturation levels. Reification is a CP technique with the availability to transform a constraint to a 1/0 variable where 1 refers to the constraint being true and 0 otherwise.

The research goal of this paper is to develop a constraint programming model that is capable to remove the detected concurrence events by considering bounded time stamp adjustments on strategic agreed points of the aircraft trajectory and to identify saturation events.

The paper is organised as follows: Section 2 explains the methodology description to retrieve the input for the CP model. Section 3.1 describes the constraint model that has been developed to tackle the problem considering one degree of freedom and Section 3.2 outlines the extension of the model introducing speed changes between segments. Section 4 discusses the observations that were made when applying the model and Section 5 extends the model with an analysis of the solver using reification constraints for potential saturation situations. Conclusions and opportunities for further work are discussed in Section 6.

3 Methodology description

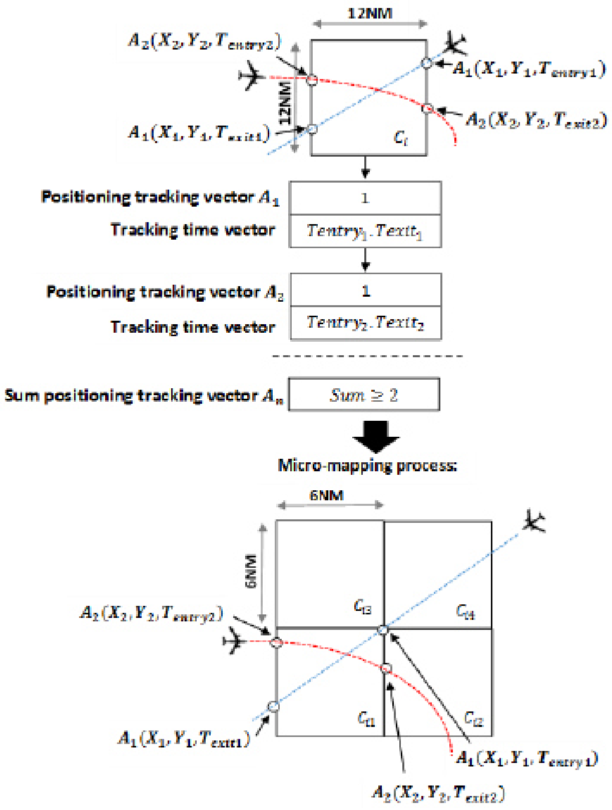
The detection of tight trajectory interdependencies is realised in three constituent processes which will be presented in the following. The output of the detection of tight trajectory interdependencies allows their resolution using CP.

To identify tight trajectory interdependencies, the entire European airspace is classified into so-called collective microregions. Based on the TBO concept, the en-route trajectories are initially projected on a discrete grid by flight level covering the European airspace (longitude -20 and 30 degrees and latitude of 0 to 80 degrees). The trajectories and relevant flight information must be supported by computationally efficient algorithms and databases. The concept of airspace sectorisation is based on previous research as for example stated in Trandac et al.(2005).

3.1 Macro-mapping process

One objective of the search algorithm is to detect tight trajectory interdependencies to solve the scalability problem and to design a computational efficient algorithm. Therefore, the airspace is first divided into macrocells with a size of 12NM (22, 224 km). The position tracking is stored as a vector. Each position in the vector can assume a binary value of 0 or 1. Presence in a cell is represented by 1 and absence by 0 (see Figure 2). The entry and exit times of an aircraft into a cell are registered and stored as a vector.

Figure 2 Macro- and micro mapping process (see online version for colours)



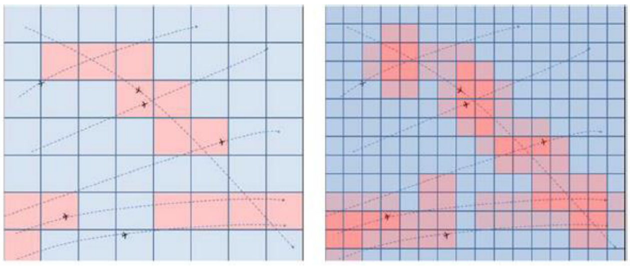
3.2 Micro-mapping process

After the initial mapping, the macrocells with an occupancy rate equal or greater than two are partitioned for the identification of collective microregions that is the set of cells showing potential concurrence events (Barnier and Allignol 2012). The microcells represent square cells of 6NM that are in use by at least two aircraft simultaneously. The size 6NM (11.112 km) has been chosen with respect to the safety distance two aircraft always have to respect. For collective microregions, entry times and exit times are used to determine the size of the overlap or clearance between aircraft pairs. As can be seen in Figure 2, the process is identical to the previously presented macro-mapping process considering smaller cells. To improve the reliability of the collective microregion identification, the four areas located on the boundaries of surrounding cells are analysed using a shifting process to detect any concurrence event between trajectories in neighbour cells.

3.3 Filtering process

Finally, the detected concurrence events are filtered for each pair of aircraft. The outcome after the filter is the ‘‘tightest’’ potential concurrence events for each pair of aircraft (see Figure 3), since aircraft that have enough clearance to guarantee the safety minimum do not have to be considered in the resolution of tight trajectories, as will be explained in the following section.

Figure 3 Detection of ‘collective microregions’ (see online version for colours)



4 Constraint model

CP is a powerful paradigm for representing and solving a wide range of combinatorial problems. In the last few decades it has attracted much attention among researchers due to its flexibility and its potential for solving hard combinatorial problems in areas such as scheduling, planning, timetabling and routing. CP combines strong theoretical foundations (e.g., techniques originated in different areas such as mathematics, artificial intelligence, and operations research) with a wide range of application in the areas of modelling heterogeneous optimisation and satisfaction problems. Moreover, the nature of CP provides other important advantages such as fast program development, economic program maintenance and efficient runtime performance. Problems are expressed in terms of three entities: variables, their corresponding domains, and constraints relating them.

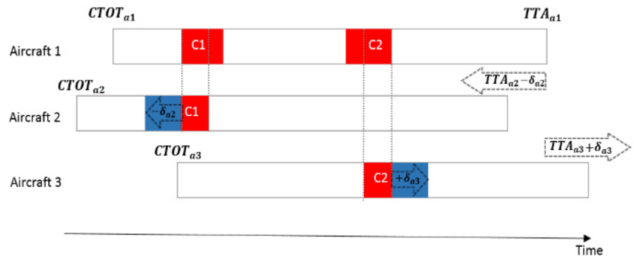
The presented approach recognises the synchronisation problem as a scheduling problem, similar to some extent to the well-known job shop scheduling problem (JSSP) or for the single objective optimisation constrained scheduling problem (SOCSP) (Tselios et al., 2013). Roughly, this problem consists of allocating the proper resources to the list of jobs facing an optimisation goal to minimise some temporal, productivity or efficiency cost function.

Similar to the JSSP or the SOCSP, the available cells as portions of the airspace can be considered as the existing resource and the aircraft as the jobs that are performed requiring the resource.

4.1 Tight trajectories interdependencies resolution

In this CP model version, the tight trajectory resolution is modelled using one control action: shifting the entire trajectory by the delay applied on the CTOT as is can be seen in Figure 4. The CTOT of aircraft 2 is shifted ahead of its original schedule and the CTOT of aircraft 3 is delayed to guarantee that all three aircraft arrive to the cell in conflict at different time windows.

Figure 4 Resolution of tight trajectory interdependencies with one freedom degree (see online version for colours)



Note: C = conflict.

After the mapping and filtering process we obtain a representation of all the conflicts that must be removed by the optimisation model. This information is then processed in order to define the following data structures.

Let A be the set of aircraft, C the set of cells belonging to one collective microregion and $c_a = <c, a>$ the pairing between the aircraft a using a given cell c at the microregions. The pairings $c_a \in C_A$ is defined as:

$$C_A = \{< c, a > | \forall c \in C, \forall a \in A\}$$

Finally, the time occupancy of the cell c by aircraft a is defined by the two parameters:

$$\begin{aligned} c_a^{te} &\equiv \textit{entry time} \\ c_a^{ts} &\equiv \textit{exit time} \end{aligned} \tag{1}$$

4.1.1 Decision variables

To ensure that the departure adjustment of the aircraft remain in the defined timeframe of [–5, 10] minutes, the integer decision variable δ_a is defined as the delay applied to the CTOT of aircraft a:

$$\delta_a \in [-\delta_{\min}, \delta_{\max}],$$

where $\delta_{\min} = 5$ and $\delta_{\max} = 10$, expressed in minutes, sets the domain for the delay decision variable.

The use of a cell by an aircraft is modelled by means of interval decision variables. Interval decision variables represent time periods whose duration and position in time are unknown in the optimisation problem. The interval is characterised by a start value, an end value and a size. Addressing this concept as a scheduling problem, the interval is the time during which something happens (e.g., an activity is carried out). In this case, it is the occupancy of the cell c by an aircraft a modelled by the interval decision variable:

$$P_{ca} = [s_{c_a}, e_{c_a}), \quad \forall c_a \in C_A \tag{2}$$

and the size:

$$sz(P_{c_a}) = e_{c_a} - s_{c_a} \left(= c_a^{ts} - c_a^{te}\right)$$

where s_{c_a} and e_{c_a} are the interval start and end time respectively.

Since the shifting applied to the trajectory to avoid the proximate events is determined by the delay δ_a and no speed adjustments are accepted, the domain of the interval variable can be defined as [see also equation (1)]

$$P_{c_a} \in \left[c_a^{te} - \delta_{\min}, c_a^{ts} + \delta_{\max}\right], \forall c_a \in C_a \tag{3}$$

As illustrated in Figure 4, the time occupancy of the cell that is involved in a concurrence event remains constant. The aircraft take-off time instants are shifted according to the delay δ that is applied to avoid the concurrence event in the cell.

Each of the cells can be occupied by one aircraft at a time, so the aircraft going through the cell must be sequenced accordingly. The decisions on the use of conflicting cells are modelled by sequence variables, which are defined as:

$$F_c = \{P_{c_a} | c_a \in C_A\}, \quad \forall c \in C \tag{4}$$

with the permutation π of the sequence variable F_c and the function:

$$\pi : F_c \to [1, m]$$

where $m = |F_c|$ is the number of aircraft going through the cell c. The elements of the sequence meet the following conditions:

$$P_{c_{ai}} \neq P_{c_{aj}} \Rightarrow \pi(P_{c_{ai}}) = \pi(P_{c_{aj}}), \forall P_{c_{ai}}, P_{c_{aj}} \in F_c$$

4.1.2 Constraints

Two constraints are identified in order to define the space of feasible solutions. The first constraint aims to model the shifting of every interval variable according to the applied delay:

$$s\left(P_{c_a}\right) = c_a^{te} + \delta_a, \forall c_a \in C_A \tag{5}$$

where the function $s(\cdot)$ is defined as the interval start time (aircraft entry to cell c):

$$s\left(P_{c_a}\right) = s_{c_a} \tag{6}$$

The second constraint is the *no overlap* constraint that imposes a set of interval variables to not overlap each other in time. In this case, all aircraft in a cell c with proximate events should have no overlap:

$$NO\left(F_c\right) \Leftrightarrow \pi\left(P_{c_i}\right) < \pi\left(P_{c_j}\right) \Rightarrow e\left(P_{c_i}\right) \le s\left(P_{c_j}\right) \tag{7}$$

where the function $e(\cdot)$ is defined as the interval end time (aircraft exit from cell c):

$$e\left(P_{c_a}\right) = e_{c_a} \tag{8}$$

and the no overlap is guaranteed for the proximate event P_{c_i} at a position prior to any P_{c_j} by constraining its exit time to be lower or equal to the entry time of the subsequent proximate events P_{c_j}.

4.1.3 Optimisation goal

The objective function was chosen to enhance adherence with a synchronisation mechanism. Although flexible, it does not preserve the TTA at the destination airport. Therefore, it aims to minimise the differences between actual take-off times and the planned change of the CTOTs.

The optimisation goal of the solution is to minimise the total aircraft delays, and it is formulated as follows:

$$\sum_{a=1}^{n} \left|\delta_a\right| \tag{9}$$

where a refers to the aircraft and δ_a is the delay applied.

The whole optimisation model is listed here:

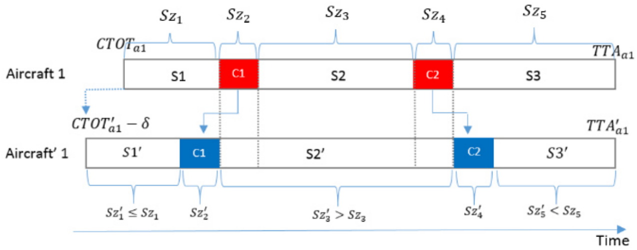
A set of aircraft
C set of cells at a collective microregion
$C_A = \{<c, a>| \forall c \in C, \forall a \in A\}$
d.v. $\delta_a \in [-\delta_{\min}, \delta_{\max}], \forall \in A$
d.v. $P_{c_a} \in \left[c_a^{te} - \delta_{\min}, c_a^{ts} + \delta_{\max}\right], \forall c_a \in C_a$
d.v. $F_c = \left\{P_{c_a} \middle| c_a \in C_A\right\}, \forall c \in C$
minimise $\sum_{a=1}^{n} \left|\delta_a\right|$
subject to {
$s\left(P_{c_a}\right) = c_a^{te} + \delta_a, \forall c_a \in C_A$
$\forall P_{c_i}, P_{c_j} \in F_c$
$NO\left(F_c\right) \Leftrightarrow \pi\left(P_{c_i}\right) < \pi\left(P_{c_j}\right) \Rightarrow e\left(P_{c_i}\right) \le s\left(P_{c_j}\right)$
}

This model was applied and successfully solved an over-stressed realistic scenario. The scenario was composed of a set of 4,010 real 4D trajectories in the European airspace for a time window of 2 hours, showing more than 65,000 proximate events. Nevertheless, the modified trajectories do not meet the TTA, since no speed adjustment possibility is included in this model. The next section extends the model to improve the RBT adherence of the modified trajectories.

4.2 Tight trajectory interdependencies resolution with speed adjustments

TTA adherence is a main objective to enhance capacity at arrival airports. Clearly, the TTA cannot be preserved by shifting the CTOT and therefore, the full trajectory. The TTA in ATM has a small margin of [–1, 1] minute. Therefore, its compliance is of high importance. To meet these conditions, the model described in Section 3.1 has been extended by introducing the concept of segments for describing the full trajectory from departure (CTOT) until the arrival time to the destination (TTA). Figure 5 illustrates this concept. For instance, aircraft 1 in the figure is divided into five segments: C1 and C2 represent the concurrence events while S1, S2 and S3 are the segments between the concurrence events. In the modified trajectory, the segment S1' is shifted according to the applied delay on the CTOT to avoid the first concurrence event while S3' is shortened in time by speed change in order to preserve the TTA within the margin. The intermediate segment S2’ is extended in time by flying with reduced speed to avoid concurrence event C2.

Figure 5 Resolution of tight trajectory interdependencies with speed change (see online version for colours)



Notes: C = conflict; S = segment; Sz = size.

The speed adjustments are realised under the condition that the segments between proximate events are of a certain minimum duration. That allows for the introduction of a speed change that is efficient in terms of fuel consumption and in the effect on the resolution of the conflict while trying to preserve the TTA.

New data structures are included to model the trajectory segments for speed adjustments. Let $\hat{g}_i^a$ be a segment of the aircraft a trajectory. Therefore, the RBT can be noted as:

$$RBT_a = \left\{\hat{g}_i^a\right\}, \quad i = 1..p(a)$$

where $p(\cdot)$ is the number of segments required for describing the trajectory. For instance, Figure 7 shows the trajectory segments of aircraft 1, represented as, $RBT_a = \{S1, C1, S2, C2, S3\}$ with

$$s(\hat{g}_i^a) = \text{start time of } \hat{g}_i^a,$$
$$e(\hat{g}_i^a) = \textit{end time of } \hat{g}_i^a$$

where the functions $s(\cdot)$ and $e(\cdot)$ yield the start and end times of the corresponding RBT segments [see equations (7) and (9) for the function definition].

Finally, the concept of segment elasticity $l(\hat{g}_i^a)$ is introduced to denote the allowed speed variation as a percentage of the $\hat{g}_i^a$ segment duration $sz(\hat{g}_i^a)$.

4.2.1 Additional decision variables

In this new CP model approach, the duration of the entire flight becomes an unknown itself, since CTOT can be delayed while keeping the intent to preserve the TTA.

A decision interval variable G_a is introduced for representing the entire flight:

$$G_a = [s_a, e_a)$$

where s_a will be the take-off time and e_a the arrival time in the solution.

Secondly, the interval variables representing the segments of the G_a solution trajectory are modelled. Let g_i^a be the interval variable:

$$g_i^a = [s(g_i^a), e(g_i^a))$$

and the size of the g_i^a segment is:

$$sz(g_i^a) = e(g_i^a) - s(g_i^a)$$

The domain of the g_i^a segment can be defined as:

$$sz(g_i^a) \in \left[sz(\hat{g}_i^a) - l(\hat{g}_i^a),\, sz(\hat{g}_i^a) + l(\hat{g}_i^a)\right] \tag{10}$$

Note that in this model version, interval duration can differ from RBT segment duration, since some elasticity is enabled by the bounded speed changes, whereas the domain for the interval start and end time cannot be specified, since their values at the solution are a combination of the take-off delay and the bounded speed adjustments.

Finally, a sequence variable T_a is introduced to set the relationship between the trajectory segments g_i^a and the entire trajectory G_a:

$$T_a = \left\{g_i^a \middle| \forall a \in A, i \in 1..p(a)\right\}$$
$$\pi : T_a \to [1, n] \tag{11}$$
$$g_i^a \neq g_j^a \Rightarrow \pi(g_i^a) \neq \pi(g_j^a), \forall g_i^a, g_j^a \in T_a$$

4.2.2 Additional Constraints for speed change

The duration of the flight is determined by the constraint of the take-off time and the time of arrival.

$$s(G_a) = CTOT_a \pm \delta_a \tag{12}$$

$$e(G_a) \in [TTA_a - 1, TTA_a + 1] \tag{13}$$

The relationship between the flight interval variable and its segments is modelled by the following *span* condition:

$$span(G_a, \{g_i^a\}), \forall a \in A, \forall g_i^a \in T_a$$

This constraint sets the following time relationship among the interval variables:

$$\begin{cases} s(G_a) = \min\limits_{i \in [1,\, p(a)]} \left(\{s(g_i^a)\}\right) \\ e(G_a) = \max\limits_{i \in [1,\, p(a)]} \left(\{e(g_i^a)\}\right) \end{cases} \tag{14}$$

The constraint *span* states that the interval flight spans over all present intervals from the set segments. That is, interval flight G_a starts together with the first present segment interval and ends together with the last one.

Additionally, the following three constraints are set to order the trajectory segments:

1 The no overlap constraint to ensure that interval variables do not overlap each other.

$$NO(G_a) \Leftrightarrow \pi(g_i^a) < \pi(g_j^a) \Rightarrow e(g_i^a) \le s(g_j^a) \tag{15}$$

2 The constraint that one segment has to start before the next:

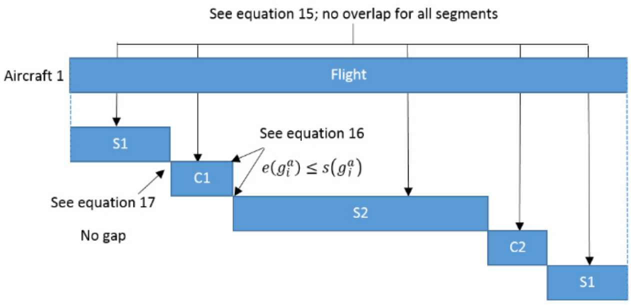
$$e(g_i^a) \le s(g_j^a), \forall i, j : i \le j \tag{16}$$

3 The constraint that ensures that the start of segment *j* results after the end of segment *i*.

$$e(g_i^a) = s(g_j^a), \forall i, j : j = i + 1 \tag{17}$$

The graphical representation of these three constraints is shown in Figure 6. Aircraft 1 has a flight duration and the projection of the segments onto the flight duration with the three conditions is shown.

Figure 6 Representation of function flight and RBT segments (see online version for colours)



Finally, the P_{c_a} interval variable, that is used in combination with the sequence variable F_c to remove the concurrence events at cell *c*, must be linked with the concurrence segments of the trajectory T_a (e.g. C1 and C2 in

Figure 6), since they represent the same time windows. This is accomplished by the following constraint:

$$\begin{cases} s\left(g_i^a\right)=s\left(P_{c_a}\right) & s\left(\hat{g}_i^a\right)=c_a^{te} \\ & \Leftrightarrow \\ e\left(g_i^a\right)=e\left(P_{c_a}\right) & e\left(\hat{g}_i^a\right)=c_a^{ts} \end{cases} , \forall c_a \in c_A$$

4.2.3 *Objective function*

The constraint in equation (10) binds to the TTA attainment. However, it might happen that no solution is found because time adjustment is bounded so it is possible that the required delay δ_a cannot be compensated by the speed adjustments. For this reason, the TTA constraint is relaxed. The following logical function is added:

$$L\left(G_a\right)=\begin{cases}1, & e\left(G_a\right) \notin \left[TTA_a-1, TTA_a+1\right] \\ 0, & \text{otherwise}\end{cases}$$

With this function, the number of TTA violations can be counted. Minimising this function and combining it with the objective function stated in equation (9), a new combined objective function is defined. This function minimises the total delay of the aircraft take-offs and minimises the number of TTA violations. The following equation weighs both objectives to get the optimisation goal:

$$\min w_1 \sum_{a=1}^{n}\left|\delta_a\right| + w_2 \sum_{a=1}^{n} L\left(G_a\right) \tag{18}$$

The extended optimisation model is listed here:

A set of aircraft
C set of cells at a collective microregion
$C_A = \{<c, a>| \ \forall c \in C, \forall a \in A\}$
$RBT_a = \left\{\hat{g}_i^a \middle| \forall a \in A, i = 1\right\}$

d.v. $\delta_a \in [-\delta_{\min}, \delta_{\max}], \forall \in A$

d.v. $P_{c_a} \in \left[c_a^{te} - \delta_{\min}, c_a^{ts} + \delta_{\max}\right], \forall c_a \in C_a$

d.v. $F_c = \left\{P_{c_a} \middle| c_a \in C_A\right\}, \forall c \in C$

d.v. $G_a, \forall a \in A$

d.v. $g_i^a, \forall a \in A, \forall i \in 1..p(a) : sz\left(g_i^a\right) \in \begin{bmatrix} sz\left(\hat{g}_i^a\right) - l\left(\hat{g}_i^a\right), \\ sz\left(\hat{g}_i^a\right) + l\left(\hat{g}_i^a\right) \end{bmatrix}$

d.v. $T_a = \left\{g_i^a\right\}, \forall a \in A$

minimise

$$w_1 \sum\nolimits_{a=1}^{n} \left|\delta_a\right| + w_2 \sum\nolimits_{a=1}^{n} L\left(G_a\right)$$

subject to {

$s\left(g_i^a\right) = CTOT_a \pm \delta_a \forall a \in A$

$\forall P_{c_i}, P_{c_j} \in F_c$

$NO\left(F_c\right) \Leftrightarrow \pi\left(P_{c_i}\right) < \pi\left(P_{c_j}\right) \Rightarrow e\left(P_{c_i}\right) \leq s\left(P_{c_j}\right)$

$span\left(G_a, \left\{g_i^a\right\}\right), \forall a \in A, \forall g_i^a \in T_a$

$\forall a \in A, \forall i, j \in 1..p(a)$

$NO\left(G_a\right) \Leftrightarrow \pi\left(g_i^a\right) \leq \pi\left(g_j^a\right) \Rightarrow e\left(g_i^a\right) \leq s\left(g_j^a\right)$

$e\left(g_i^a\right) \leq s\left(g_j^a\right) : i \leq j$

$e\left(g_i^a\right) = s\left(g_j^a\right) : j = i + 1$

$$\begin{cases} s\left(g_i^a\right)=s\left(P_{c_a}\right) & s\left(\hat{g}_i^a\right)=c_a^{t_e} \\ & \Leftrightarrow \\ e\left(g_i^a\right)=e\left(P_{c_a}\right) & e\left(\hat{g}_i^a\right)=c_a^{t_s} \end{cases} , \forall c_a \in c_A$$

}

5 Application of the model

The model was applied to an over-stressed realistic scenario. The scenario was composed of a set of 4,010 real 4D trajectories in the European airspace for a time window of 2 h. In this work, we assumed TBO without uncertainties. In this context, the trajectories were discretised at each second, and each position was specified in terms of geographic coordinates and a time stamp. This scenario was designed and analysed in the STREAM project (Ranieri et al. 2011), a EUROCONTROL SESAR WP-E project. The CP model has been implemented with the ILOG Optimisation Suite (IBM, 2015) and the following results were obtained.

5.1 *Macro and micro mapping*

The detection of concurrence events in this paper is based on the algorithms and results presented at Nosedal et al. (2014) and Nosedal et al. (2015). The aforementioned 2h scenario leads to the detection of collective microregions. These microregions have been used to find the optimal CTOT adjustments and speed changes to reduce proximate events and, therefore, possible ATC interventions.

In Figure 7(a) the en-route traffic through the collective microregions is shown. The cells with potential concurrence events are detected based on the RBT trajectories of those aircraft ready to depart, but still on ground, according to their CTOT. Therefore, en-route trajectories are conflict free at the given time instant.

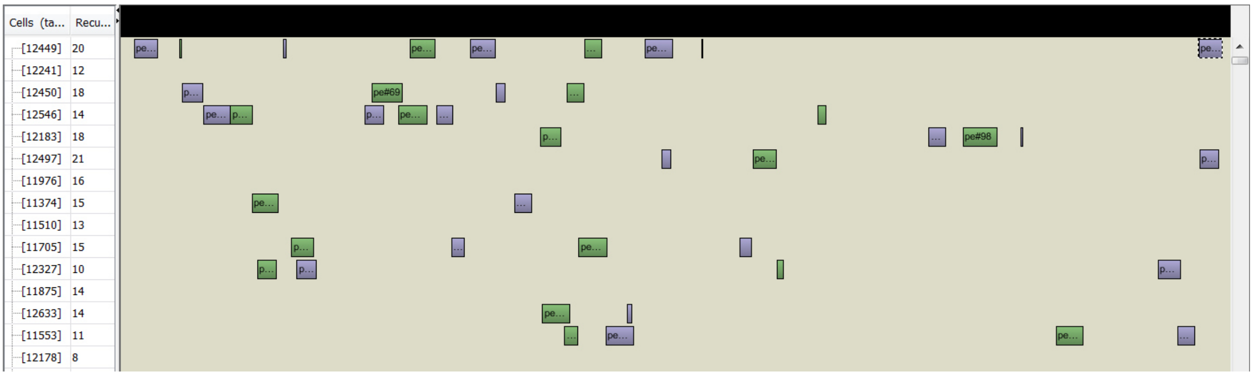
Figure 7(b) shows the situation found when the grounded aircraft depart according to their RBT CTOT. As it can be seen, for instance, at cells 12,241, 12,449 and 12,450 among others, concurrence events will appear between several aircraft if they depart according to their CTOT. In this case, aircraft regulations could be issued by ATM or, later on, ATC interventions would be needed to remove the proximate events caused by the inserted traffic.

5.2 *Trajectory adjustments*

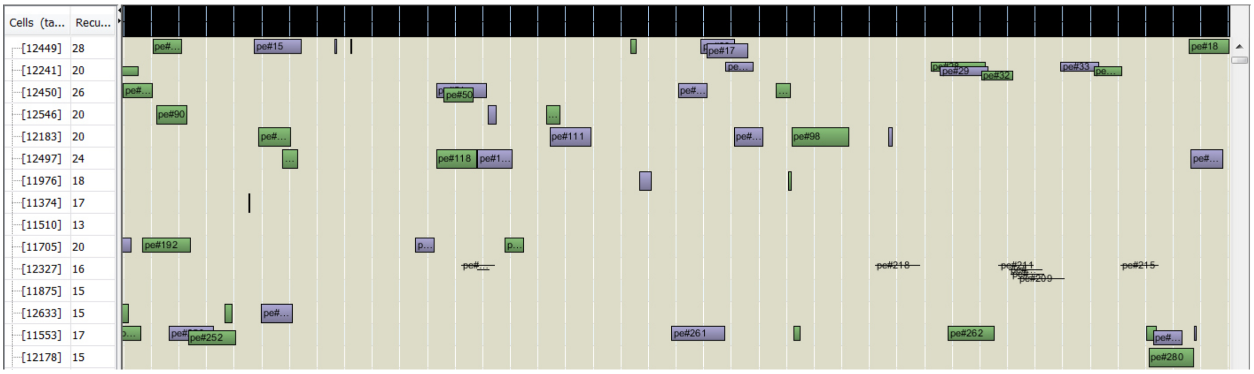
The proposed CP model is used to determine the proper adjustments on the CTOT and aircraft trajectories to remove the potential concurrence events.

As Figure 8 illustrates, all the potential concurrence events are removed by applying a combination of bounded delays on CTOT and/or speed adjustments, leading to a conflict free scenario.

Figure 7 Gantt diagrams showing the traffic through the cells with potential concurrence events, diagram (a) shows the conflict free en-route traffic and (b) shows the emerging conflict after inserting the departing traffic for the same time period (see online version for colours)



(a)



(b)

Figure 8 The diagram shows the conflict free solution after applying small adjustments on CTOT and segment' speed (see online version for colours)

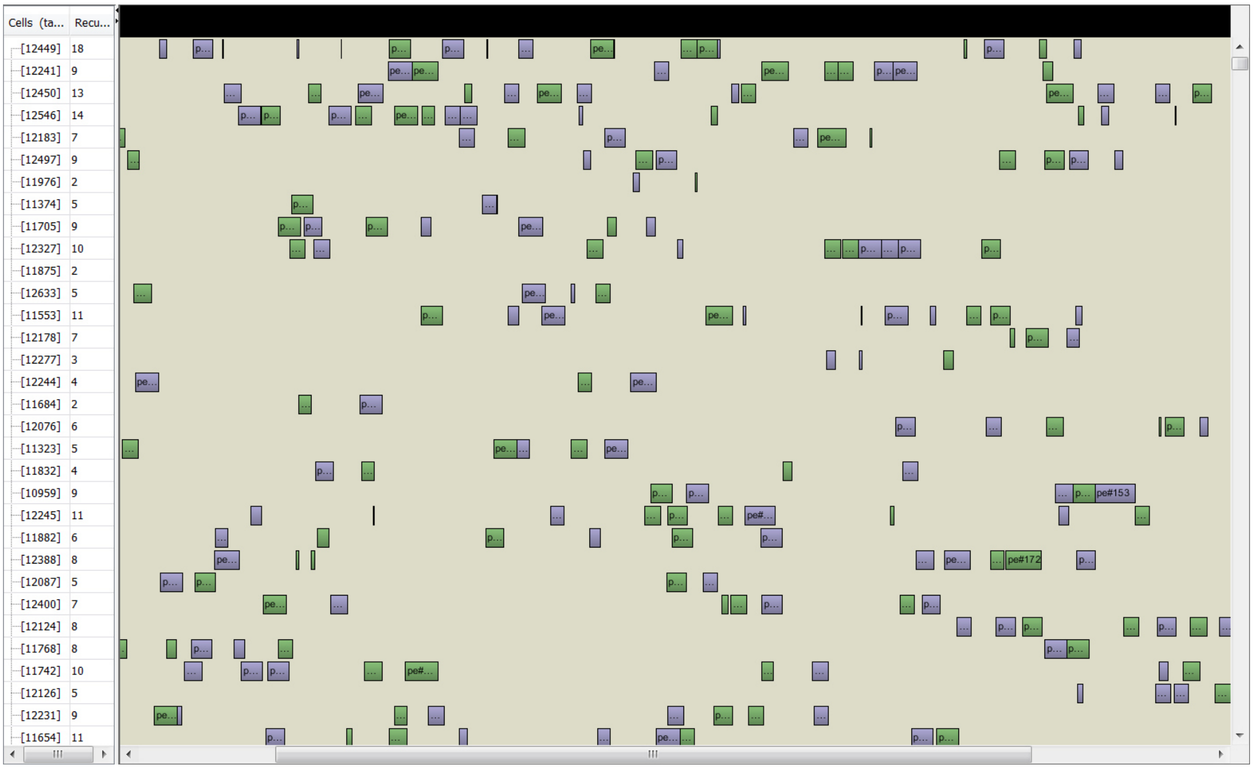
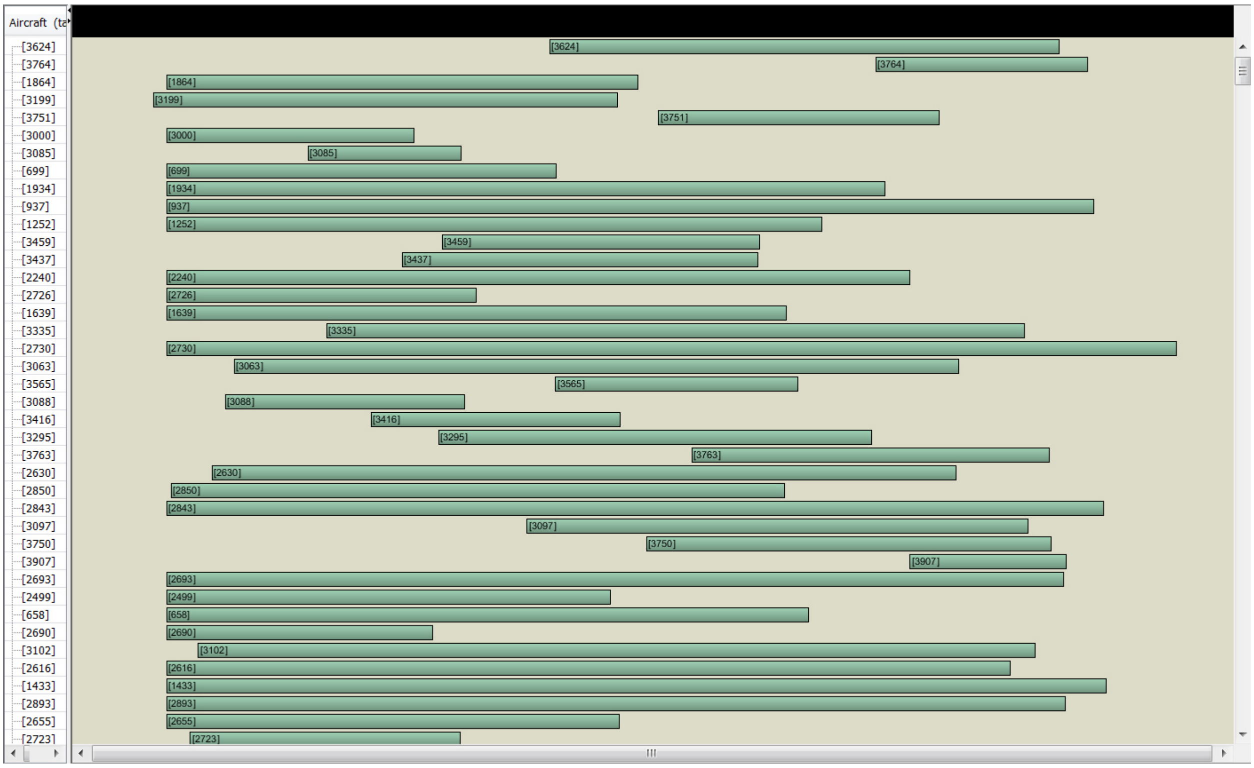
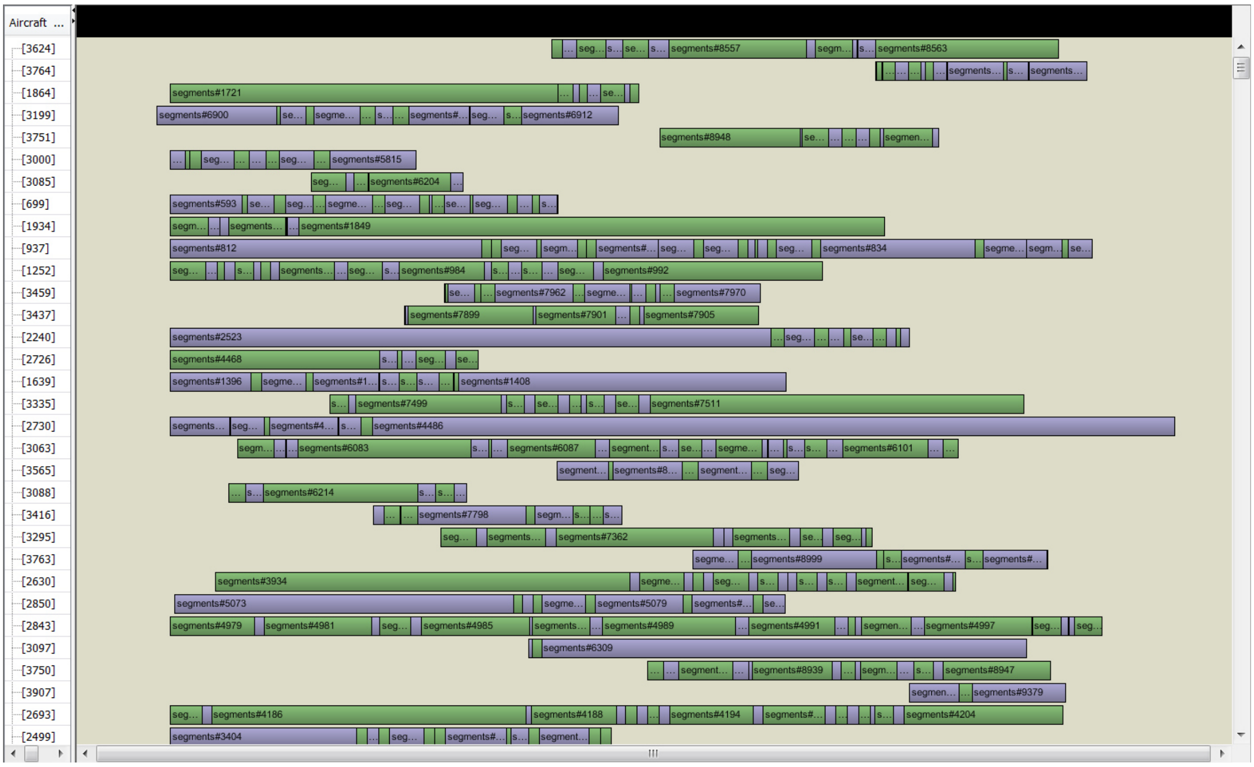


Figure 9 (a) The Gantt diagram shows the full flight interval of the aircraft in potential concurrence events (b) The diagram shows their segment structure (see online version for colours)



(a)



(b)

The bounded adjustments impose the actual take-off time to be within the [–5, 10] minutes of the aircraft CTOT [see equation (13)] and the speed adjustments to be less than 10% of the RBT proposed by the airline [see equation (11)]. Furthermore, Figure 9(a) shows the full flight interval of the aircraft and Figure 9(b) shows their segment structure.

The ILOG CP solver was limited to 180 seconds to get the best suboptimal solution. All the experiments were performed on a Windows 10 computer with an Intel Core I7 CPU 2,30 GHz and 16GB RAM.

5.3 *Observations*

Since the adjustments on CTOT and speed changes are bounded, the TTA fulfilment cannot be ensured. As stated at equation (18), the TTA requirement was relaxed, and its fulfilment was included in the optimisation goal. The used weights were $w_1 = 10\%$ and $w_2 = 90\%$, so giving priority to the TTA preservation.

Figure 10 shows the correlation between the actual time of arrival (ATA) compared to the TTA with respect to the applied CTOT delay. As it can be observed, in most of the cases the bounded speed adjustments are not enough to recover the effect of the applied delays. In Figure 11 it is shown the absolute numbers of aircraft are not able to meet their TTA with respect to the applied delay. There are two main reasons leading to these results.

Figure 10 Correlation between TTA violation and the delays applied to the aircraft takeoff times (see online version for colours)

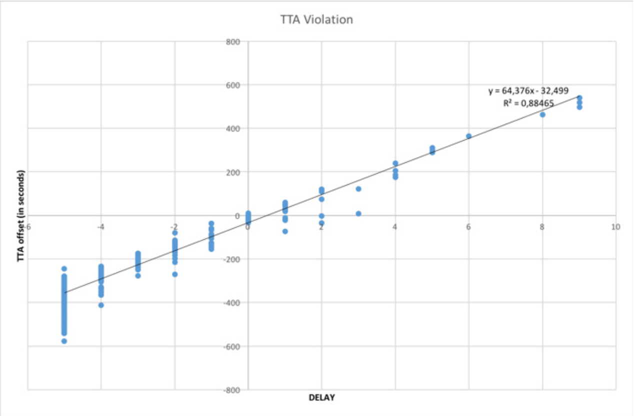
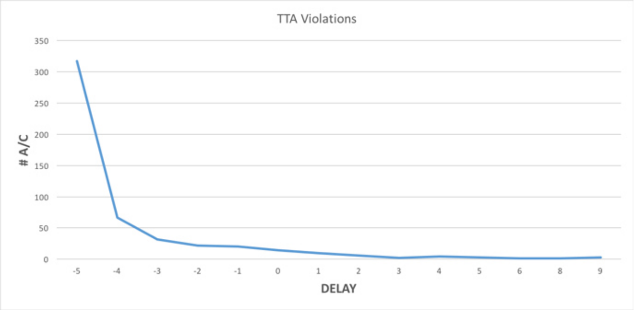


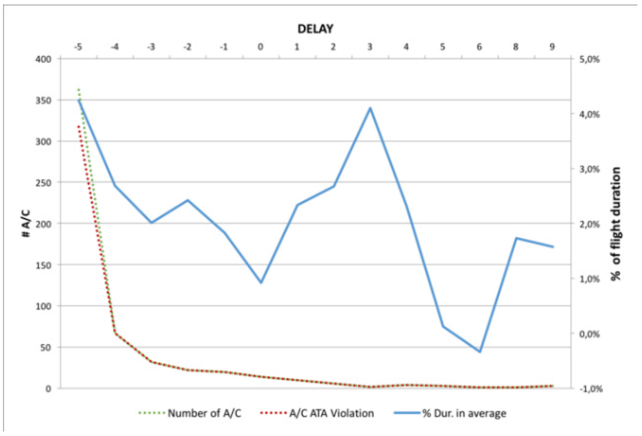
Figure 11 A/C not meeting their TTA with respect to the applied CTOT delay (see online version for colours)



The first observation is that most of the aircraft are moved ahead of their CTOT. This is a consequence of the solver search strategy (Van Beek, 2006), since time to get the suboptimal solution was limited to 180 seconds. This strategy is set by default and first takes the smallest values in the decision variable domains. In this case, this value is −5 minutes for the δ_a delay.

The second reason can be explained from the graph represented in Figure 12. The number of aircraft that do not meet their TTA is tightly related to the applied delay, as it can be observed from dotted curves. However, the average modification on flight duration is not related to the applied delay. The margins enabled by the bounded speed adjustments are not enough for compensating the applied delays. This fact could be overcome only if, first, solutions with lower absolute delays can be found (better search strategy) and, second, if the aircraft trajectory allows a bigger absolute elasticity. The second condition does not depend on the solution method, but on the duration of the flight and on the number and relative positions of the proximate events involved.

Figure 12 Blue line represents the average modification of flight duration with respect to the applied delay; dotted lines represent the number of A/C with the respective delay and the number of A/C not meeting their TTA (see online version for colours)



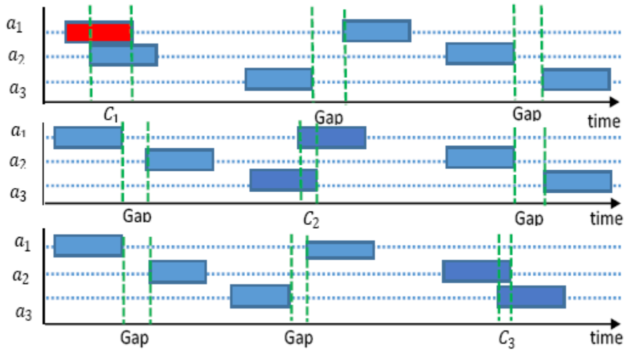
6 Saturation event

In CP, modelling is the process of representing a problem as a Constraint Satisfaction Problem (CSP). In the previous explained model the problem is to fit all the values of the RBT. For example, the no-overlap of segments that is limited by the decision variable of the allowed green delay constraints the solving of all the concurrence events. In the process of satisfying all constraints while respecting the search domain, it might happen that no solution exists.

There are several route interdependencies that could cause a failure due to a cycle of delays or advances in their take-off times. For example, the interdependencies between the three trajectories represented in Figure 14 can lead to applying a sequence of take-off delays or advances inside the departure slot that would lead to a useless time-shifting.

In Figure 13 the overlap and clearances of an over-constraint topology in the form of a triangle is represented using a temporal representation. The triangle is formed of three conflict cells that are all interconnected. The corner points of the triangle are the concurrence events between a_1 and a_2, between a_1 and a_3 and between a_2 and a_3.

Figure 13 Temporal representation of an over-constraint triangle topology (see online version for colours)



In the following an approach is presented to identify the occurrence of saturation by introducing the CP modelling technique *reification*.

To model this problem, logical connectives between constraints are required e.g. the RBT should span over the whole duration of the flight AND one segment of the RBT must start before the next. In some cases, it is useful to apply a NOT constraint to the problem which in CSP is done by the means of reification. The reification of a constraint C produces another constraint C_r, such that C_r has an extra Boolean variable r in its variable set, and (in any solution) r is set to true if and only if the original constraint C is satisfied, see (Jefferson et al., 2017).

To model the clearance that exists between aircraft that are involved in a concurrence event a new decision variable is introduced representing the clearances h of all conflicts.

$$h \in [C_A] \tag{19}$$

To identify a possible saturation level of cells with the above presented model, a binary decision variable X_a with the domain $X_a = [0, 1]$ for all aircraft a has been introduced. Furthermore, the separation constraint [see equations (21) and (22)] and the departure constraint [see equation (20)] have been modified introducing the concept of reification.

The constraint that models the shifting of every interval variable has been modified in a way that if X_a has the value 0, then the CTOT is not modified, see equation (20).

$$s\left(P_{c_a}\right) = c_a^{te} + \delta_a * X[a], \forall c_a \in C_A \tag{20}$$

Also, the separation constraint of aircraft passing through one cell was separated in a way that the RBT is only modified if and only if X_a has the value 1, see equations (21) and (22). Furthermore, the occupancy of the cell c by an aircraft a with its size defined by the start and end time has been extended in a way that if the overlap of the aircraft was solved by the no overlap constraint than the exit time of the first aircraft a_i using the cell c is smaller than the entry time of the second aircraft a_j and the difference between the entry time of a_j and the exit time of a_i is greater than the clearance h of all conflicts and the other way around.

$$\begin{aligned} X_{c_i} = 1 \wedge X_{cj} = 1 \wedge e\left(P_{c_i}\right) \le s\left(P_{c_j}\right) \\ \Rightarrow s\left(P_{c_j}\right) - e\left(P_{c_i}\right) \ge h[C_A] \end{aligned} \tag{21}$$

$$\begin{aligned} X_{c_i} = 1 \wedge X_{cj} = 1 \wedge e\left(P_{c_j}\right) \le s\left(P_{c_i}\right) \\ \Rightarrow s\left(P_{c_i}\right) - e\left(P_{c_j}\right) \ge h[C_A] \end{aligned} \tag{22}$$

The optimisation goal of the solution is to maximise the minimum clearance (w_1) and at the same time to minimise the number of relaxed trajectories since the sum of X_i is maximised (w_2). The objective function is formulated as follows:

$$\max w_1 \min_{c_a} h[C_A] + w_2 \sum X_i \tag{23}$$

The extended optimisation model is listed here:

A set of aircraft
C set of cells at a collective microregion
$C_A = \{<c, a>| \forall c \in C, \forall a \in A\}$
$RBT_a = \left\{\hat{g}_i^a \middle| \forall a \in A, i = 1..p(a)\right\}$
d.v. $\delta_a \in [-\delta_{\min}, \delta_{\max}], \forall a \in A$
d.v. $P_{c_a} \in \left[c_a^{te} - \delta_{\min}, c_a^{ts} + \delta_{\max}\right], \forall c_a \in C_a$
d.v. $F_c = \left\{P_{c_a} \middle| c_a \in C_A\right\}, \forall c \in C$
d.v. $G_a, \forall a \in A$
d.v. $g_i^a, \forall a \in A, \forall i \in 1..p(a) : sz\left(g_i^a\right) \in \begin{bmatrix} sz\left(\hat{g}_i^a\right) - l\left(\hat{g}_i^a\right), \\ sz\left(\hat{g}_i^a\right) + l\left(\hat{g}_i^a\right) \end{bmatrix}$
d.v. $T_a = \left\{g_i^a\right\}, \forall a \in A$
d.v. $h \in [C_A]$
minimise

$$w_1 \min_{c_a} h[C_A] + w_2 \sum X_i$$

subject to {

$$s\left(g_i^a\right) = CTOT_a \pm \delta_a \forall a \in A$$

$$\forall P_{c_i}, P_{c_j} \in F_c$$

$$NO\left(F_c\right) \Leftrightarrow \pi\left(P_{c_i}\right) < \pi\left(P_{c_j}\right) \Rightarrow e\left(P_{c_i}\right) \le s\left(P_{c_j}\right) = true$$

$$e\left(P_{c_i}\right) \le s\left(P_{c_j}\right) \Rightarrow s\left(P_{c_j}\right) - e\left(P_{c_i}\right) \ge h[C_A]$$

$$e\left(P_{c_j}\right) \le s\left(P_{c_i}\right) \Rightarrow s\left(P_{c_i}\right) - e\left(P_{c_j}\right) \ge h[C_A]$$

$$span\left(G_a, \left\{g_i^a\right\}\right), \forall a \in A, \forall g_i^a \in T_a$$

$$\forall a \in A, \forall i, j \in 1..p(a)$$

$$NO\left(G_a\right) \Leftrightarrow \pi\left(g_i^a\right) \le \pi\left(g_j^a\right) \Rightarrow e\left(g_i^a\right) \le s\left(g_j^a\right)$$

$$e\left(g_i^a\right) \le s\left(g_j^a\right) : i \le j$$

$$e\left(g_i^a\right) = s\left(g_j^a\right) : j = i + 1$$

$$\left\{\begin{array}{lcl} s\left(g_i^a\right)=s\left(P_{c_a}\right) & & s\left(\hat{g}_i^a\right)=c_a^{t_e} \\ & \Leftrightarrow & \\ e\left(g_i^a\right)=e\left(P_{c_a}\right) & & e\left(\hat{g}_i^a\right)=c_a^{t_s} \end{array}\right. ,\forall c_a \in c_A$$

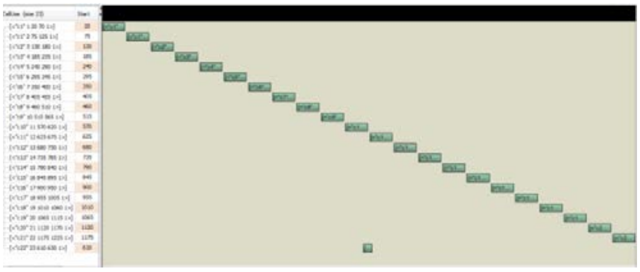
}

6.1 *Application and experimental results*

The algorithm was applied on a set of 23 aircraft that in attempt to solve the conflict scenarios reach saturation level. That is for example to model a very frequent throughput of one specific cell of traffic. The traffic in this cell is en-route and therefore, the departure time cannot be modified anymore. In this traffic an aircraft that is ready to depart must be merged within the departure modification slot of [–5, 10] minutes.

After running the algorithm, the throughput of the cell reveals that the conflict could not be solved as demonstrated in Figure 14. The throughput of the aircraft en-route through the cell is performed sequentially with no overlaps. The aircraft that has to be inserted in the en-route traffic (see the segment on the bottom in the middle of Figure 15) remains in conflict with the other traffic.

Figure 14 Unsolved conflict (see online version for colours)



The high throughput in the cell that is occupied with en-route traffic does not allow to insert the departing aircraft within its CTOT domain of [–5, 10] minutes in such a way that the concurrence event can be resolved. In such a situation, the aircraft either would have to be handled directly by ATM or the green delay domain of [–5, 10] minutes would have to be exceeded to find a suitable best solution.

7 Conclusions

In this work, a CP model is presented for solving the concurrence events that might occur when the departure traffic is inserted into the en-route traffic. Compared to other models, this research is based on the partitioning of the sky into cells that are used to detect concurrence events and mark the design of the here presented CP mitigation tool. The model has been proved in a realistic and overstressed scenario and it has been able to find suboptimal solutions in a timeframe of 180 seconds for all the performed experiments.

The model constraints ensure that all the proximate events are resolved by introducing small time adjustment both on the CTOT and relevant TTO's while maximising the adherence to the RBT's. Although the model is not able to ensure that the ATM concept of preserving the TTA in a strict time frame is met, the CP solver can find solutions that remove all the conflicts reducing the number of potential ATC interventions.

The concept of preserving the TTA has been relaxed and the objective function penalises the TTA violation. The reason for this is the limit of the trajectory elasticity, since speed adjustments are bounded to a percentage of the total RBT duration.

Finally, the concept of reification was introduced to the model to detect potential saturation levels of conflict scenarios. Due to strict safety requirements in air traffic the detection of these saturations is essential to ensure that all potential conflicts are eliminated. With the presented approach, conflict scenarios that reach saturation levels can be detected and relaxed so that other safety nets can take action to eliminate the concurrence event. In this approach only a small example of the application of reification was given. Future research has to be done to design traffic scenarios and identify geometries of aircraft that lead to saturation levels or deadlocks.

Finally, further research is required to apply different search strategies on different traffic scenarios favouring the selection of adjustments close to zero in first term. This way speed adjustment efforts are expected to be smaller. Moreover, further research is suggested to understand the cause of saturations and to develop best strategies on how to solve them.

8 Acronyms

ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
AU	Airspace User
CP	Constraint Programming
CSP	Constraint Satisfaction Problems
CTOT	Calculated-Take-Off Time
DST	Decision Support Tool
JSSP	Job Shop Scheduling Problem
LH	Linear Holding
SOCSP	Single objective optimisation constrained scheduling problem
TBO	Trajectory Based Operation
TTA	Target Time of Arrival
TTO	Time-To-Overfly
RBT	Reference Business Trajectory
4DT	4-dimensional trajectories

Acknowledgements

This research is supported by the European Union's Horizon 2020 research and innovation program. The Project related to this research is PARTAKE 'Cooperative departures for a competitive ATM network service' with Grant Agreement No. 699307. Opinions expressed in this paper reflect author's views only.

References

Adacher, L., Flamini, M. and Romano, E. (2017) 'Rerouting algorithms solving the air traffic congestion advanced PID tuning based on the modulus optimum method for real systems rerouting algorithms solving the air traffic congestion', *International Conference on Applied Mathematics and Computer Science AIP Conference Proceedings AIP Conference Proceedings*, Vol. 10, No. 10, pp.20053–20060 [online] https://doi.org/10.1063/1.4981993 (accessed 25 November 2017).

Arfi, F., Ilié, J.M. and Saidouni, D.E. (2016) 'Solving preemptive job-shop scheduling problems using a true concurrency model', *International Journal of Simulation and Process Modelling*, Vol. 11, Nos. 3/4, p.292 [online] http://www.inderscience.com/link.php?id=78507 (accessed 24 November 2017).

Barnier, N. and Allignol, C. (2009) '4D-trajectory deconfliction through departure time adjustment', *Europe Air Traffic Management Research and Development Seminar* [online] https://hal-enac.archives-ouvertes.fr/hal-00938231/document (accessed 23 April 2017).

Barnier, N. and Allignol, C. (2012) 'Trajectory deconfliction with constraint programming', Vol. 27, No. 3, pp.291–307 [online] https://hal-enac.archives-ouvertes.fr/hal-00935206/document (accessed 23 April 2017).

Bessiere, C. (2006) 'Constraint propagation', *Handbook of Constraint Programming*, Chapter 3, pp.29–83, Elsevier.

Cook, A. (2007) *European Air Traffic Management: Principles, Practice and Research* [online] https://books.google.es/books/about/European_Air_Traffic_Management.html?id=vQ9LG6TWl9oC&redir_esc=y (accessed 11 May 2017).

Eurocontrol (2017) *Flight Planning|Eurocontrol* [online] http://www.eurocontrol.int/articles/flight-planning (accessed 27 March 2017).

Huang, Z. and Zhao, H. (2016) 'Construction resource scheduling with chaotic particle swarm optimisation', *International Journal of Simulation and Process Modelling*, Vol. 11, No. 1, p.1 [online] http://www.inderscience.com/link.php?id=75065 (accessed 24 November 2017).

IBM (2015) *IBM ILOG CPLEX Optimization Studio OPL Language Reference Manual*, Version 12, pp.1–152 [online] https://www.ibm.com/support/knowledgecenter/SSSA5P_12.6.2/ilog.odms.studio.help/pdf/opl_langref.pdf (accessed 4 January 2018).

Jefferson, C. et al. (2017) *Implementing Logical Connectives in Constraint Programming* [online] https://pn.host.cs.st-andrews.ac.uk/aij-watchedor-reify-paper.pdf (accessed 8 April 2017).

Marcella, S. et al. (2017) 'Scheduling models for optimal aircraft traffic control at busy airports: tardiness, priorities, equity and violations considerations', *Omega*, Vol. 67, pp.81–98 [online] http://www.sciencedirect.com/science/article/pii/S0305048316301165 (accessed 25 November 2017).

Nosedal, J. et al. (2014) 'An efficient algorithm for smoothing airspace congestion by fine-tuning take-off times', *Transportation Research Part C: Emerging Technologies*, Vol. 44, pp.171–184.

Nosedal, J. et al. (2015) 'An optimization model to fit airspace demand considering a spatio-temporal analysis of airspace capacity', *Transportation Research Part C: Emerging Technologies*, Vol. 61, pp.11–28.

Ranieri, A. et al. (2011) *STREAM – Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management Concept*, *Methodology and Tools*, December, pp.1–8, sesarinnovationdays.eu.

Sesar (2015) *The Roadmap For delivering High Performing Aviation For Europe European ATM Master Plan.*, Edition 20 [online] http://ec.europa.eu/transport/modes/air/sesar/doc/eu-atm-master-plan-2015.pdf (accessed 18 July 2016).

SKYbrary (2017) *4D Trajectory Concept – SKYbrary Aviation Safety* [online] https://www.skybrary.aero/index.php/4D_Trajectory_Concept (accessed 19 November 2017).

Tajini, R., Elhaq, S.L. and Rachid, A. (2014) 'Modelling methodology for the simulation of the manufacturing systems', *International Journal of Simulation and Process Modelling*, Vol. 9, No. 4, p.285 [online] http://www.inderscience.com/link.php?id=66372 (accessed 24 November 2017).

Trandac, H., Baptiste, P. and Duong, V. (2005) 'Airspace sectorization with constraints', *RAIRO – Operations Research*, Vol. 39, No. 2, pp.105–122 [online] http://www.rairo-ro.org/10.1051/ro:2005005 (accessed 23 April 2017).

Tselios, D.C., Savvas, I.K. and Kechadi, M.T. (2013) 'Multiple project portfolio scheduling using recurrent neural networks', *International Journal of Simulation and Process Modelling*, Vol. 8, No. 4, p.227 [online] http://www.inderscience.com/link.php?id=59421 (accessed 24 November 2017).

Van Beek, P. (2006) 'Backtracking search algorithms', *Handbook of Constraint Programming*, Chapter 4, pp.85–134, Elsevier B.V.

Xu, Y. and Prats, X. (2017) 'Including linear holding in air traffic flow management for flexible delay handling', *Europe Air Traffic Management Research and Development Seminar* [online] http://www.atmseminarus.org/seminarContent/seminar12/papers/12th_ATM_RD_Seminar_paper_139.pdf (accessed 25 November 2017).

Yan, X. and Xavier, P. (2017) 'Effects of linear holding for reducing additional flight delays without extra fuel consumption', *Transportation Research Part D: Transport and Environment*, Vol. 53, pp.388–397 [online] http://www.sciencedirect.com/science/article/pii/S1361920916308501 (accessed 25 November 2017).

Chapter 7

7. Paper 3

This paper has been presented to the Twelfth USA/Europe Air Traffic Management Research and Development Seminar (ATM2017) and was awarded the best paper reward. It shows a first approach to integrate time uncertainty to the proposed detection, analysis and mitigation methodology.

Twelfth USA/Europe Air Traffic Management Research and Development Seminar (ATM2017)

A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures

Juan J.Ramos, Nina Schefers, Marko Radanovic,
Miquel A. Piera
Dep. of Logistics and Aeronautics
Universitat Autònoma de Barcelona
Barcelona, Spain
JuanJose.Ramos@uab.es

Pau Folch
Dep. of Research and Innovation
Aslogic
Rubí, Spain
pfolch@aslogic.es

Abstract— **The lack of a proper integration of strategic ATM decision support tools with tactical ATC interventions usually generates a negative impact in the Reference Business Trajectory adherence, and in consequence affects the potential of the TBO framework. In this paper, a new mechanism to reduce the amount of ATC interventions at tactical level while preserving ATFM planned operations is presented as part of the PARTAKE project. The project fosters adherence of air space user's trajectory preferences enhancing Trajectory Based Operation (TBO) concepts by identifying tight interdependencies between trajectories and introducing a new mechanism to improve aircraft separation at the hot spots. The underlying philosophy is to capitalize present freedom degrees between layered Air Traffic Management (ATM) planning tools, when sequencing departures at airports by considering the benefits of small time stamp changes in the assigned CTOT departures.**

Keyword- Air traffic management; Trajectory Based Operations; Decision Support Tool; Constraint Programming

I. INTRODUCTION

Air transport is an integral part of transport infrastructure and a significant sector of the economy predicted next decades with steady growth. Therefore, the identification of operational and managing policies for better performance of existing airspace procedures is important in order to cut European Air Traffic Management (ATM) costs, increase capacity and operational safety and decrease the environmental impact. The intention of this innovative approach is to design a competitive ATM system, supporting up to a certain extent the Airspace User (AU's) demands at the right time (i.e. departure slots), at the right cost (i.e. suitable level of Air Traffic Control (ATC) service) at the right place (i.e. AU's preferred trajectories) and at the right service quality (i.e. safety) without extra investments, just by removing the ATM non-added-value operations that indirectly impact on present ATM capacity.

By empowering the concept of Trajectory-based Operations (TBO) as a flexible synchronization mechanism towards an efficient and competitive ATM service a precise description of an aircraft path in space and time can be retrieved [2][7]. Under this TBO approach, airspace users should fly precise 4-dimensional trajectories (4DTs), previously agreed upon with the network manager.

The presented research is conducted in the context of the PARTAKE Exploratory Research Project supported by the European Union's Horizon 2020 research and innovation program. Europe has some of the busiest airspace in the world, managed by a network covering 11.5 million km^2 of airspace [18]. The Network Manager Operations Centre receives, processes and distributes up to 35,000 flight plans a day [3]. PARTAKE aims to improve the present demand/capacity balance in ATM by introducing small ground delays in the programed departure that will not affect the planned traffic since the slot time window assigned to each aircraft will be preserved. The major challenge PARTAKE is facing is to achieve ATC minimum tactical interventions: Reference Business Trajectories (RBT) provide an excellent source of information to identify future situations in which two or more aircraft could require ATC directives to maintain the required separation minima. PARTAKE proposes mitigation methods that are able to take into account the preferences of Airlines and Airports.

This work presents a set of tools to determine small adjustments within the $[-5,10]$ interval around the Calculated Take-Off Time (CTOT), along with bounded modifications on the flight duration, as the control actions to be taken by considering the RBT and the impact on potential ATC interventions. These actions will be calculated to mitigate the potential tight trajectory interdependencies that can emerge after inserting the traffic ready to depart. The use of Constraint Programming (CP) [9] is proposed to calculate those feasible departure configurations. CP is an emergent software technology for declarative description and effective solving of large, particularly combinatorial, problems especially involving scheduling, resource allocation, placement and planning [5][8][11].

The paper is organized as follows: Section II briefly introduces the mapping and filtering mechanism implemented to detect the trajectory interdependencies between airborne flights and the new traffic; Section III describes the CP model proposed to mitigate the detected collective micro-regions that would require ATC interventions; Section IV proposes a model to deal with time uncertainty in the RBT; Section V discusses the experimental results achieved so far; finally, some conclusions and open questions for further research are discussed in Section VI.

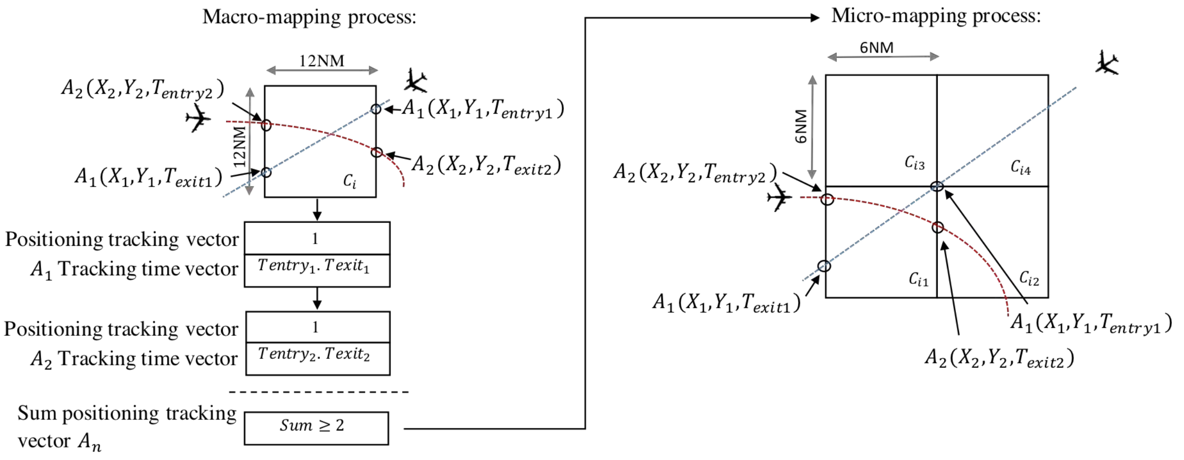


Figure 1. Macro and micro mapping process

II. DETECTION MECHANIM

The detection of tight trajectory interdependencies is realized in three constituent processes which will be presented in the following. The output of the detection of tight trajectory interdependencies enables the resolution of these interdependencies using CP.

To identify tight trajectory interdependencies, the entire European Airspace is classified into so called collective microregions. Based on the TBO concept, the enroute trajectories are initially projected on a discrete grid by flight level covering the European Airspace (longitude -20 and 30 degrees and latitude of 0 to 80 degrees). The trajectories and relevant flight information must be supported by computational efficient algorithms and databases.

A. *Macro-mapping process*

One objective of the search algorithm is to detect tight trajectory interdependencies is to solve the scalability problem and to design a computational efficient algorithm. Therefore, the airspace is divided into macrocells with a size of 12NM (22,224 km). The position tracking is stored as a vector. Each position in the vector takes a binary value. The presence in a cell is represented by 1 and absence by 0 (see Figure 1). The entry and exit times of an aircraft into a cell are registered and stored as a vector.

B. *Micro-mapping process*

After the initial mapping, the macrocells with an occupancy rate equal or greater than two are partitioned for the identification of collective microregions, that is the set of cells showing potential concurrent events. The microcells represent square cells of 6NM that are in use by at least two aircraft simultaneously [11]. The size 6NM (11.112 km) has been chosen with respect to the safety distance two aircraft always must respect. For collective microregions, entry times and exit times are used to determine the size of the overlap or clearance between aircraft pairs. As it can be seen in Figure 1, the process is identical to the previous presented macro-mapping process considering smaller cells. To ensure the reliability of the collective microregion identification, the occupancy of surrounding cells is analyzed in order to detect any concurrence event between trajectories at neighbor cells.

C. *Filtering process*

Finally, the detected concurrence events are filtered for each pair of aircraft. The outcome after the filter are the tightest potential concurrence events for each pair of aircraft (see Figure 2). This process shall filter those trajectories either losing the required clearance (separation minima) or that are in a risk of losing it after mitigation measures are applied. The filtering process is based on the collective micro-regions that were detected in the mapping process. For these collective micro-regions, entry (t_a^e) and exit (t_a^s) times are used to determine the temporal looseness, referring to the size of the overlap or clearance between aircraft pairs. The calculation of the temporal looseness H between time windows of aircraft $a_1$and a_2 in a collective micro-region is expressed as follows:

$$H = \min\left(t_{a_1}^s, t_{a_2}^s\right) - \max(t_{a_1}^e, t_{a_2}^e)$$

Concurrence events exist when H is positive, indicating an overlap, whereas events with a negative H value have a clearance time, indicating a potential concurrence event. Based on the calculation of H (the size of an overlap or clearance), it is possible to identify the tightest concurrence events, or potentially concurrence events, for each pair of aircraft.

III. MITIGATION PROCESS

The conflict mitigation process is modeled as Constraint Programming (CP) model [9]. CP is a powerful paradigm for representing and solving a wide range of combinatorial problems. In the last few decades it has attracted much attention among researchers due to its flexibility and its potential for solving hard combinatorial problems in areas such as scheduling, planning, timetabling and routing. CP combines strong theoretical foundations (e.g. techniques originated in different areas such as Mathematics, Artificial Intelligence, and

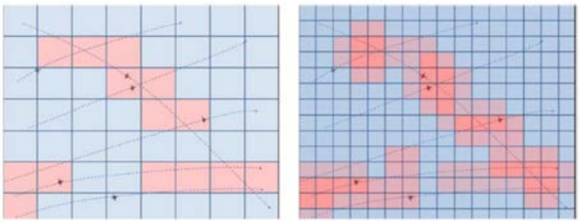


Figure 2. Detection of collective microregions at macro and micro level

Operations Research) with a wide range of application in the areas of modelling heterogeneous optimization and satisfaction problems. Moreover, the nature of CP provides other important advantages such as fast program development, economic program maintenance and efficient runtime performance. Problems are expressed in terms of three entities: variables, their corresponding domains, and constraints relating them.

The presented approach recognizes the synchronization problem as a scheduling problem, similar to some extend to the well-known Job Shop Scheduling Problem (JSSP). Roughly, this problem consists in allocating the proper resources to the list of jobs facing an optimization goal to minimize some temporal, productivity or efficiency cost function. By setting the analogy to the JSSP, the available cells as portions of the airspace can be considered as the existing resource and the aircraft as the jobs that are performed requiring the resource.

A. *Tight trajectory interdependencies resolution*

The mapping and filtering processes generate a representation of all the conflicts that must be removed by the optimization model. In a first CP model version, the tight trajectory resolution is modeled using one control action: Shifting the entire trajectory by a delay to be applied on the CTOT. As Figure 3 illustrates, the CTOT of aircraft 2 is shifted ahead of its original schedule and the CTOT of aircraft 3 is delayed to guarantee that all three aircraft arrive to the cells in conflict at different time windows.

Let A be the set of aircraft, C the set of cells belonging to one collective microregion and $c_a =< c, a >$ the pairing between the aircraft a using a given cell c at the microregions. The pairings $c_a \in C_A$ are defined as:

$$C_A = \{< c, a > \mid \forall c \in C, \forall a \in A\}$$

Finally, the time occupancy of the cell c by aircraft a is defined by the two parameters:

$$\begin{aligned} c_a^{te} &\equiv entry\ time \\ c_a^{ts} &\equiv exit\ time \end{aligned} \qquad (1)$$

1) *Decision variables*

To ensure that the departure adjustment of the aircraft remain in the defined timeframe of [-5,10] minutes, the integer decision variable δ_a is defined as the delay applied to the CTOT of aircraft a:

$$\delta_a \in [-\delta_{min}, \delta_{max}],$$

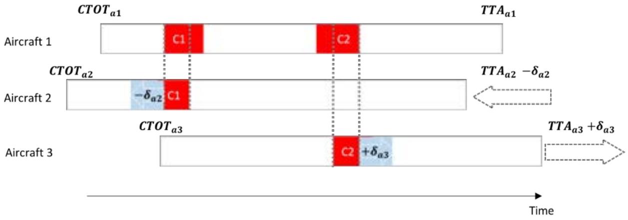


Figure 3. Resolution of tight trajectory interdependencies (C=Conflict)

where $\delta_{min} = 5$ and $\delta_{max} = 10$ minutes, sets the domain for the delay decision variable.

The use of a cell by an aircraft is modeled by means of interval decision variables. Interval decision variables represent time periods whose duration and position in time are unknown in the optimization problem. The interval is characterized by a start value, an end value and a size. Addressing this concept as a scheduling problem, the interval is the time during which something happens (e.g. an activity is carried out). In this case, it is the occupancy of the cell c by an aircraft a modeled by the interval decision variable:

$$P_{ca} = \left[s_{c_a}, e_{c_a}\right), \qquad \forall\, c_a \in C_A \qquad (2)$$

and the size:

$$sz\left(P_{c_a}\right) = e_{c_a} - s_{c_a} (= c_a^{ts} - c_a^{te})$$

where s_{c_a} and e_{c_a} are the interval start and end time respectively.

Since the shifting applied to the trajectory to avoid the proximate events is determined by the delay δ_a and no speed adjustments are accepted, the domain of the interval variable can be defined as (see also (1)):

$$P_{c_a} \in [c_a^{te} - \delta_{min}, c_a^{ts} + \delta_{max}], \forall c_a \in C_a \qquad (3)$$

As illustrated in Figure 3, the time occupancy of the cell that is involved in a concurrent event remains constant. The aircraft takeoff time instants are shifted according to the delay δ that is applied to avoid the concurrent event in the cell.

Each of the cells can be occupied by one aircraft at a time, so the aircraft going through the cell must be sequenced accordingly. The decisions on the use of conflicting cells are modeled by sequence variables, which are defined as:

$$F_c = \left\{P_{c_a} \middle| c_a \in C_A\right\}, \qquad \forall c \in C \qquad (4)$$

with the permutation π of the sequence variable F_c as the function

$$\pi: F_c \to [1, m]$$

where $m = |F_c|$ is the number of aircraft going through the cell c. The elements of the sequence meet the following conditions:

$$P_{c_{ai}} \neq P_{c_{aj}} \Rightarrow \pi\left(P_{c_{ai}}\right) = \pi\left(P_{c_{aj}}\right), \forall\, P_{c_{ai}}, P_{c_{aj}} \in F_c$$

2) *Constraints*

Two constraints are identified in order to define the space of feasible solutions. The first constraint aims to model the shifting of every interval variable according to the applied delay:

$$s\left(P_{c_a}\right) = c_a^{te} + \delta_a, \forall c_a \in C_A \tag{5}$$

where the function $s(\cdot)$ is defined as the interval start time (aircraft entry to cell c):

$$s\left(P_{c_a}\right) = s_{c_a} \tag{6}$$

The second constraint is the *no overlap* constraint that imposes a set of interval variables to not overlap each other in time. In this case, all aircraft in a cell c with proximate events should have no overlap:

$$\begin{gathered} \forall P_{c_i}, P_{c_j} \in F_c \\ NO(F_c) \Leftrightarrow \pi(P_{c_i}) < \pi(P_{c_j}) \Rightarrow e(P_{c_i}) \leq s(P_{c_j}) \end{gathered} \tag{7}$$

where the function $e(\cdot)$ is defined as the interval end time (aircraft exit from cell c):

$$e\left(P_{c_a}\right) = e_{c_a} \tag{8}$$

and the no overlap is guaranteed for the proximate event P_{c_i} at a position prior to any P_{c_j} by constraining its exit time to be lower or equal to the entry time of the subsequent proximate events P_{c_j}.

3) *Optimization goal*

The objective function was chosen to enhance adherence with a synchronization mechanism, though flexible, does not preserve the TTA at destination airport. Therefore, it aims to minimize the differences between actual takeoff times and the planned or CTOTs.

The optimization goal of the solution is to minimize the total aircraft delays, and it is formulated as follows:

$$\sum_{a=1}^{n} |\delta_a| \tag{9}$$

where a refers to the aircraft and δ_a is the delay applied. The whole optimization model is listed here:

A set of aircraft
C set of cells at a collective microregion
$C_A = \{< c, a > \mid \forall c \in C, \forall a \in A\}$
d.v. $\delta_a \in [-\delta_{min}, \delta_{max}], \forall a \in A$
d.v. $P_{c_a} \in [c_a^{te} - \delta_{min}, c_a^{ts} + \delta_{max}], \forall c_a \in C_a$
d.v. $F_c = \{P_{c_a} | c_a \in C_A\}, \ \forall c \in C$

minimize $\sum_{a=1}^{n} |\delta_a|$
subject to {
  $s\left(P_{c_a}\right) = c_a^{te} + \delta_a, \forall c_a \in C_A$
  $\forall P_{c_i}, P_{c_j} \in F_c$
    $NO(F_c) \Leftrightarrow \pi(P_{c_i}) < \pi(P_{c_j}) \Rightarrow e(P_{c_i}) \leq s(P_{c_j})$
}

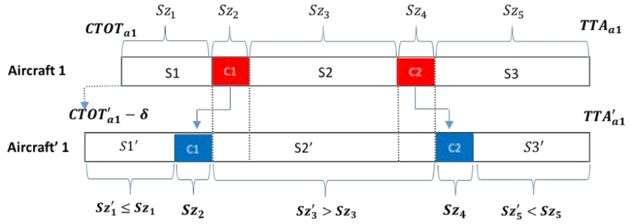


Figure 4. Resolution of tight trajectory interdependencies with speed change (C=Conflict; S=Segment; Sz=Size)

This model successfully solved an over-stressed realistic scenario. The scenario was composed of a set of 4010 real 4D trajectories in the European airspace for a time window of 2 hours, showing more than 65.000 proximate events. Nevertheless, the modified trajectories do not meet the TTA, since no speed adjustment possibility is included in this model. Next section extends the model in order to improve the RBT adherence of the modified trajectories.

B. *Tight trajectory interdependencies resolution with speed adjustments*

TTA adherence is a main objective to enhance capacity at arrival airports. Clearly, the TTA cannot be preserved by shifting the CTOT and therefore, the full trajectory. The TTA in ATM has a small margin of [-1,1] minute. Therefore, its compliance is of high importance. To meet these conditions, the model described in section 3.1 has been extended by introducing the concept of segments for describing the full trajectory from departure (CTOT) until the arrival time to the destination (TTA). Figure 4 illustrates this concept. For instance, aircraft 1 in the figure is divided into five segments: C1 and C2 represent the concurrence events while S1, S2 and S3 are the segments between the concurrence events. In the modified trajectory, the segment S1' is shifted according to the applied delay on the CTOT to avoid the first concurrence event while S3' is shortened in time by speed change in order to preserve the TTA within the margin. The intermediate segment S2' is extended in time by flying with reduced speed to avoid concurrence event C2.

The speed adjustments are realized under the condition that the segment between proximate events are of a certain minimum duration. That allows to introduce a speed change that is efficient in the sense of fuel consumption and in the effect on the resolution of the conflict while trying to preserve the TTA.

New data structures are included to model the trajectory segments for speed adjustments. Let $\hat{g}_i^a$ be a segment of the aircraft a trajectory. Therefore, the RBT can be noted as:

$$RBT_a = \{\hat{g}_i^a\}, \qquad i = 1..p(a)$$

where $p(\cdot)$ is the number of segments required for describing the trajectory. For instance, the Figure 4 shows the trajectory segments of aircraft 1, represented as $RBT_a = \{S1, C1, S2, C2, S3\}$ with

$$s(\hat{g}_i^a) = \text{start time of } \hat{g}_i^a,$$

$$\mathrm{e}(\hat{g}_i^a) = end\ time\ of\ \hat{g}_i^a$$

where the functions $s(\cdot)$ and $e(\cdot)$ yield the start and end times of the corresponding RBT segments. See (6) and (8) for the function definition.

Finally, the concept of segment elasticity $l(\hat{g}_i^a)$ is introduced to denote the allowed speed variation as a percentage of the $\hat{g}_i^a$ segment duration $sz(\hat{g}_i^a)$.

1) Additional decision variables

In this extended CP model approach, the duration of the entire flight becomes an unknown itself, since CTOT can be delayed while keeping the intend to preserve the TTA.

A decision interval variable G_a is introduced for representing the entire flight:

$$G_a = [s_a, e_a)$$

where s_a will be the takeoff time and e_a the arrival time in the solution.

Secondly, the interval variables representing the segments of the G_a solution trajectory are modeled. Let g_i^a be the interval variable:

$$g_i^a \ = [s(g_i^a\ ), e(g_i^a\ ))$$

and the size of the g_i^asegment is

$$sz(g_i^a\ ) = e(g_i^a\ ) - s(g_i^a\ )$$

The domain of the g_i^a segment can be defined as:

$$sz(g_i^a) \in [sz(\hat{g}_i^a) - l(\hat{g}_i^a), sz(\hat{g}_i^a) + l(\hat{g}_i^a)] \qquad (10)$$

Note that in this model version, interval duration can differ from RBT segment duration, since some elasticity is enabled by the bounded speed changes. The domain for the interval start and end time cannot be specified, since their values at the solution are a combination of the takeoff delay and the bounded speed adjustments.

Finally, a sequence variable T_a is introduced to set the relationship between the trajectory segments g_i^a and the entire trajectory G_a:

$$\begin{aligned} &T_a = \{g_i^a \mid \forall a \in A, i \in 1..p(a)\} \\ &\pi: T_a \to [1, n] \\ &g_i^a \neq g_j^a \Rightarrow \pi(g_i^a) \neq \pi(g_j^a), \forall g_i^a, g_j^a \in T_a \end{aligned} \qquad (11)$$

2) Additional Constraints for speed change

The duration of the flight is determined by the constraint of the takeoff time and the time of arrival.

$$s(G_a\ ) = CTOT_a \pm \delta_a \qquad (12)$$

$$e(G_a\ ) \in [TTA_a - 1, TTA_a + 1] \qquad (13)$$

The relationship between the flight interval variable and its segments is modeled by the following *span* condition:

$$span(G_a, \{g_i^a\}), \forall a \in A, \forall g_i^a \in T_a$$

This constraint sets the following time relationship among the interval variables:

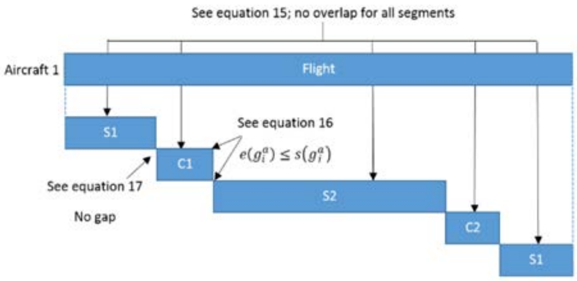


Figure 5. Representation of decision variable flight and RBT segments

$$\begin{cases} s(G_a) = \min\limits_{i \in [1,p(a)]}(\{s(g_i^a)\}) \\ e(G_a) = \max\limits_{i \in [1,p(a)]}(\{e(g_i^a)\}) \end{cases} \qquad (14)$$

The constraint *span* states that the interval flight spans over all present intervals from the set segments. That is, interval flight G_a starts together with the first present segment interval and ends together with the last one.

Additionally, the following three constraints are set to order the trajectory segments:

1. The *no overlap* constraint to ensure that interval variables to not overlap each other.

$$NO(G_a) \Leftrightarrow \pi(g_i^a) < \pi(g_j^a) \Rightarrow e(g_i^a) \leq s(g_j^a) \qquad (15)$$

2. The constraint that one segment has to start before the next:

$$e(g_i^a) \leq s(g_j^a), \forall i, j: i < j \qquad (16)$$

3. The constraint that ensure that the start of segment j results after the end of segment i.

$$e(g_i^a) = s(g_j^a), \forall i, j: j = i + 1 \qquad (17)$$

The graphical representation of this three constraints is shown in Figure 5. Aircraft 1 has a flight duration and the projection of the segments onto the flight duration with the three conditions is shown.

Finally, the P_{c_a} interval variable, that is used in combination with the sequence variable F_c to remove the concurrence events at cell c, must be linked with the concurrence segments of the trajectory T_a (e.g. C1 and C2 in in Figure 5), since they are representing the same time windows.

This is accomplished by the following constraint:

$$\begin{cases} s(g_i^a) = s(P_{c_a}) \\ e(g_i^a) = e(P_{c_a}) \end{cases} \Leftrightarrow \begin{matrix} s(\hat{g}_i^a) = c_a^{t_e} \\ e(\hat{g}_i^a) = c_a^{t_s} \end{matrix}, \forall c_a \in c_A$$

3) Objective function

The constraint in (13) binds to the TTA attainment However, it might happen that no solution is found because time adjustment is bounded so it is possible that the required delays δ_a cannot be compensated by the speed adjustments. For this reason, the TTA constraint is relaxed.

The following logical function is added:

$$L(G_a) = \begin{cases} 1, & e(G_a) \notin [TTA_a - 1,\ TTA_a + 1] \\ 0, & \text{otherwise} \end{cases}$$

With this function, the number of TTA violations can be counted for introducing its minimization as an objective that can be combined with the objective function stated in (9) to minimize the total delay of the aircraft takeoffs. The following equation weights both objectives to get the optimization goal:

$$\min w_1 \sum_{a=1}^{n} |\delta_a| + w_2 \sum_{a=1}^{n} L(G_a) \tag{18}$$

The extended optimization model is listed here:

A set of aircraft
C set of cells at a collective microregion
$C_A = \{< c, a > \mid \forall c \in C, \forall a \in A\}$
$RBT_a = \{\hat{g}_i^a \mid \forall a \in A,\ i = 1..p(a)\}$
d.v. $\delta_a \in [-\delta_{min}, \delta_{max}], \forall a \in A$
d.v. $P_{c_a} \in [c_a^{te} - \delta_{min}, c_a^{ts} + \delta_{max}], \forall c_a \in C_a$
d.v. $F_c = \{P_{c_a} | c_a \in C_A\},\ \forall c \in C$
d.v. $G_a,\ \forall a \in A$
d.v. $g_i^a,\ \forall a \in A,\ \forall i \in 1..p(a):$
$sz(g_i^a) \in [sz(\hat{g}_i^a) - l(\hat{g}_i^a), sz(\hat{g}_i^a) + l(\hat{g}_i^a)]$
d.v. $T_a = \{g_i^a\}, \forall a \in A$

minimize
$w_1 \sum_{a=1}^{n} |\delta_a| + w_2 \sum_{a=1}^{n} L(G_a)$
subject to {
$s(g_i^a) = CTOT_a \pm \delta_a\ \forall a \in A$
$\forall P_{c_i}, P_{c_j} \in F_c$
$NO(F_c) \Leftrightarrow \pi(P_{c_i}) < \pi(P_{c_j}) \Rightarrow e(P_{c_i}) \leq s(P_{c_j})$
$span(G_a, \{g_i^a\}), \forall a \in A, \forall g_i^a \in T_a$
$\forall a \in A,\ \forall i, j \in 1..p(a)$
$NO(G_a) \Leftrightarrow \pi(g_i^a) < \pi(g_j^a) \Rightarrow e(g_i^a) \leq s(g_j^a)$
$e(g_i^a) \leq s(g_j^a) : i \leq j$
$e(g_i^a) = s(g_j^a) : j = i + 1$
$\begin{cases} s(g_i^a) = s(P_{c_a}) \\ e(g_i^a) = e(P_{c_a}) \end{cases} \Leftrightarrow \begin{matrix} s(\hat{g}_i^a) = c_a^{te} \\ e(\hat{g}_i^a) = c_a^{ts} \end{matrix}, \forall c_a \in c_A$
}

IV. DEALING WITH UNCERTAINTY

Considering the ATM sources of uncertainty (parameters of aircraft models in trajectory prediction, weather, failure of ATC systems, cancellation of flights, etc.) and the degree of safety required in PARTAKE, a rolling horizon model scope should be considered to handle reasonable amounts of uncertainty.

The flight management system (FMS) provides the primary navigation, flight planning, optimized route determination and enroute guidance for the aircraft. The guidance function of the FMS ensures that a flight within TBO concept will flight its RBT. But some deviations may occur both in time and space as a consequence of the mentioned causes. The time uncertainty is defined as the inability to exactly determine in which instant of time an aircraft will overfly a certain fixed spot in the space.

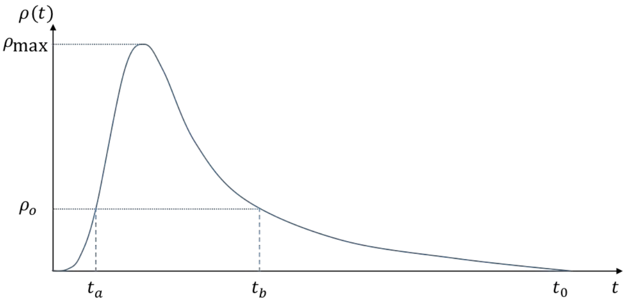


Figure 6. Evolution of $\boldsymbol{\rho(t)}$ while FMS corrects the time diversion

The space uncertainty, which would be defined in the same way, shall not be taken into account since with the space discretization (mapping) done by the conflict detection, is considered to be solved: PARTAKE considers the effects on potential conflicts due to lateral deviations from RBT to be absorbed by the size of the cells (6 NM). That is, any deviation bellow 1 mile will result in the same conflicts detected at the mapping process.

However, time differences between the enroute flights with respect to their corresponding RBT can be detected when the CTOT of the flights ready to depart is to be calculated. These differences may affect the time window occupancy of the cells in conflict as defined in (1), so that the action to be taken for mitigating the potential conflicts can be affected too.

More formally, let be $\gamma(t) \in \mathbb{R}^3$ the RBT and $\bar{\gamma}(t) \in \mathbb{R}^3$ the actual flown trajectory. Then, under the TBO concept we will expect that $\|\gamma(t) - \bar{\gamma}(t)\|_2 \approx 0$ at least in most cases. The actual state of airborne flights is conducted every 5 minutes. When an along-track deviation is detected, ρ is defined as the time difference existent between the actual position and the predefined position in the RBT. That is, if $\|\gamma(t) - \bar{\gamma}(t)\|_2 \neq 0$ is observed, then $\rho \in \mathbb{R}$ will be defined satisfying:

$$\|\gamma(t) - \bar{\gamma}(t + \rho)\|_2 = 0 \tag{19}$$

This work focuses on those deviations that may occur in time as a consequence of the effect of the wind. Two possibilities are under consideration when a ρ is detected:

1. The FMS guidance functionality has not yet acted because ρ is less than the alert value set on it.
2. The FMS is correcting ρ changing some aircraft flight parameters.

Therefore, ρ is defined as a time function $\rho(t)$ that describes the time diversion between the RBT and the actual flown trajectory as a function of time. As shown in Figure 6, it is assumed that $\rho(t)$ at the begining will increase depending on the wind until the maximum diversion allowed by the FMS is reached. Then the FMS corrections will force $\rho(t)$ to decrease until the condition $\|\gamma(t) - \bar{\gamma}(t)\|_2 \approx 0$ is reached again. When a $\rho_0$is observed, the most conservative period $[t_a, t_0]$ is selected for considering the duration of the time diversion.

A. *Estimation of the time uncertainty*

Four dimensional navigation is based on reaching a three dimensional waypoint at a required time of arrival by changing the aircraft flight profile. In this context several variables and parameters are involved in the concept of changing a flight profile. According to [10], airspeed is considered as the most important control variable in order to achieve a waypoint at a given time of arrival. The time that an aircraft spends moving from an initial point $x_1 = (lat, lon)$ to a final point $x_2 = (lat, lon)$ can be represented as follows:

$$t = \frac{1}{\beta} \int_{x1}^{x2} \frac{\partial x}{V_a(z)} \qquad (20)$$

where V_a is the true airspeed of the aircraft at a given altitude, z is the altitude and β is a conversion factor from *knots* to *feet/seconds*. The along-track wind effect has to be taken into account for time computation. The wind produces an important change of the airspeed of the aircraft and this could affect the estimation of the time of arrival. The effect of the along-track wind over the aircraft airspeed in cruise level is associated with two elements [10][17]:

1. The direction of the wind with respect to the aircraft. Depending of the relationship between the heading of the along-track wind and the aircraft, it is called tailwind or headwind.
2. The magnitude of the along-track wind which represents the constant velocity of the wind at a given altitude (cruise altitude).

The along-track component of wind in the horizontal plane can be represented as follows (equation parameters are defined in Table 1):

$$w(z) = V_W(z) \cdot cos|B(z) - H_W(z) \pm \delta| \qquad (21)$$

By combining (20) and (21), the resultant equation used to compute the time of an aircraft flight between an initial point and a final point with constant velocity, is as follows:

$$t = \frac{1}{\beta} \int_{x_1}^{x_2} \frac{\partial x}{V_a(z) + V_W(z) \cdot cos|B(z) - H_W(z) \pm \delta|} \qquad (22)$$

By integrating (22), the result is the time estimation equation with wind effect:

$$t = \frac{1}{\beta} \frac{[x_2 - x_1]}{V_a(z) \pm V_W(z) \cdot cos|B(z) - H_W(z) \pm \delta|} \qquad (23)$$

TABLE 1 PARAMETERS FOR ESTIMATING WIND EFFECTS

Constant	Details
V_W	Speed of the wind at a given altitude
H_W	Heading of the wind at a given altitude
δ	Factor to correct the magnetic north to true north
B	Bearing of the aircraft's track

Equation (23) can be used to estimate the minimum time in which an aircraft can fly from the initial point to the final point at true airspeed. Therefore, the time to the next collective micro-region of the delayed flight can be estimated from its current observed position and true airspeed, determining whether the time diversion is affecting the future concurrence events or not. Furthermore, using (23), the available weather data and taking into account factors such as aircraft particular characteristics and the maximum operational values allowed by the FMS system a model for $\rho(t)$ can be postulated [1][15].

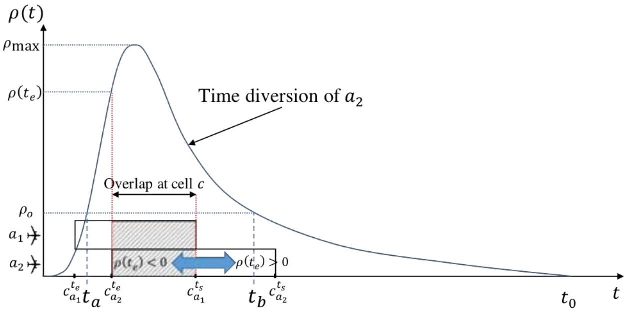


Figure 7. Effects of time diversion on conflict window

When the following condition holds:

$$\|\gamma(t) - \bar{\gamma}(t)\|_2 \neq 0, t \in [t_a, t_0] \qquad (24)$$

For every occupancy time window overlaping the period $[t_a, t_0]$, the new entry time to the micro-region can be recalculated from the estimated $\rho(t_e)$ as illustrated in Figure 7. The following modification is introduced in the CP model replacing (1):

$$\begin{aligned} c_a^{te} + \rho(t_e) &\equiv entry\ time \\ c_a^{ts} + \rho(t_e) &\equiv exit\ time \end{aligned} \qquad (25)$$

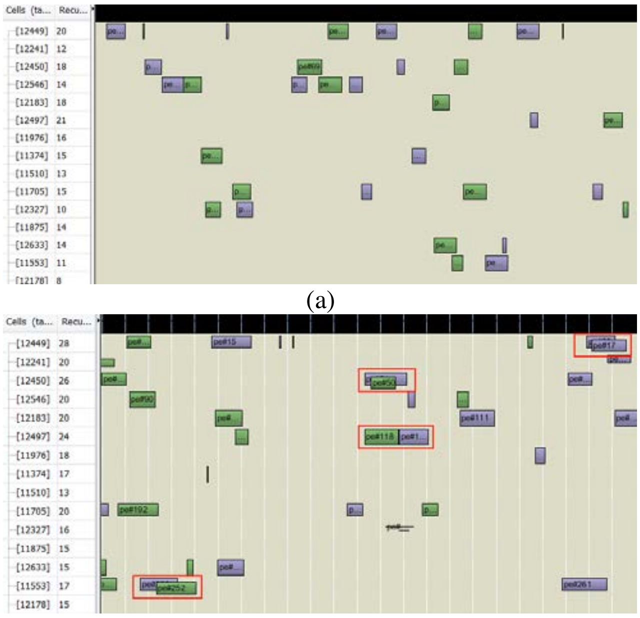
V. RESULTS

The model was applied to an over-stressed realistic scenario. The scenario was composed of a set of 4010 real 4D trajectories in the European airspace for a time window of 2 hours. In these experiments, we assumed RBT without uncertainties. In this context, the trajectories were discretized at each second, and each position was specified in terms of geographic coordinates and a time stamp. This scenario was designed and analyzed in the STREAM project [16], a EUROCONTROL SESAR WP-E project. The CP model has been implemented with the ILOG Optimization Suite [6] and the following results were obtained.

A. *Macro and Micro Mapping*

The detection of the concurrence events in this paper is based on the algorithms and results presented at [12][13] and [14]. The mapping process of the aforementioned scenario is described in these works, leading to the detection of the collective micro-regions that have been used in this work to find the optimal adjustments on CTOT and speed changes to reduce proximate events and, therefore, ATC interventions.

In Figure 8 (a) the enroute traffic through the collective micro-regions is shown. The Gantt diagram represents the time frame occupancy of the cells by each aircraft with the potential concurrence events detected from the RBT trajectories. Enroute trajectories are conflict free at the given time instant.



(a)

(b)

Figure 8. Gantt diagrams showing the traffic through the cells with potential concurrence events. Diagram (a) shows the conflict free en-route traffic and (b) shows the emerging conflict after inserting the departing traffic for the same time period

The Figure 8 (b) shows the situation found when grounded aircrafts depart according to their RBT CTOT. As it can be seen at the red framed cells (e.g. 12449 or 12450), concurrence events will appear between several aircrafts if they depart according to their CTOT. In this case, aircraft regulations could be issued by ATM or, later on, ATC interventions would be needed to remove the proximate events caused by the inserted traffic.

B. *Trajectory adjustments*

The proposed CP model is used to determine the proper adjustments on the CTOT and aircraft trajectories to remove the potential concurrence events.

As Figure 9 illustrates, all the potential concurrence events are removed by applying a combination of bounded delays on CTOT and/or speed adjustments, leading to a conflict free scenario. The bounded adjustments impose the actual takeoff time to be within the [-5,10] minutes of the aircraft CTOT as shown in (12) and the speed adjustments to be less than 10% of the RBT proposed by the airline (10). The ILOG CP solver was limited to 180 seconds to get the best suboptimal solution. All the experiments were performed on a Window 10 computer with an Intel Core I7 CPU 2,30 GHz and 16GB RAM.

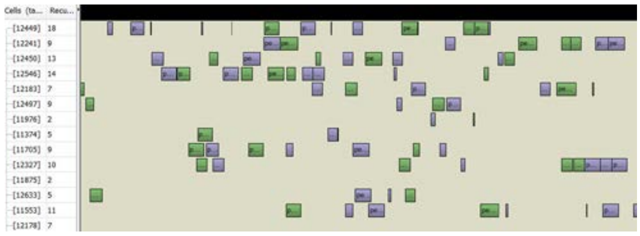


Figure 9. The diagram shows the conflict free solution after applying small adjustments on CTOT and speed.

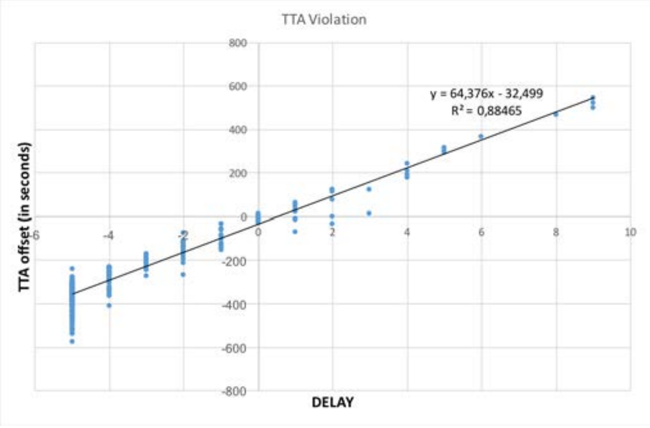


Figure 10. Correlation between TTA violation and the delays applied to the aircraft takeoff times.

C. *Solution analysis*

Since the adjustments on CTOT and speed changes are bounded, the TTA fulfilment cannot be ensured. As stated in (18), the TTA requirement was relaxed, and its fulfilment was included in the optimization goal. The used weights were $w_1 = 10\%$ and $w_2 = 90\%$, so giving priority to the TTA preservation.

The Figure 10 shows the correlation between the actual time of arrival (ATA) compared to the TTA with respect to the applied CTOT delay. As it can be observed, in most of the cases the bounded speed adjustments are not enough to recover the effect of the applied delays. In Figure 11 the absolute numbers of aircraft not able to meet their TTA with respect to the applied delay is shown. There are two main reasons explaining this results.

The first observation is that most of the aircraft are moved ahead of their CTOT. This is a consequence of the solver search strategy [19], since time to get the suboptimal solution was limited to 180 seconds. This strategy is the default one and first takes the smallest values in the decision variable domains. In this case, this value is -5 minutes for the δ_a delay. Further research is required to define search strategies leading to better solutions.

The second reason can be explained from the curves at Figure 12. The number of aircraft not meeting their TTA is

Figure 11. A/C not meeting their TTA with respect to the applied CTOT delay.

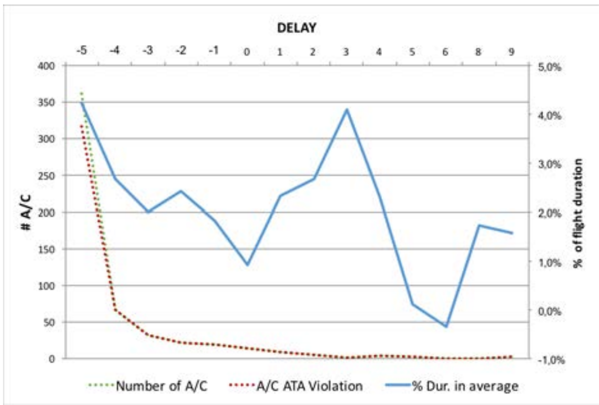


Figure 12. The blue line represents the average modification of flight duration with respect to the applied delay; dotted lines represent the number of A/C with the respective delay and the number of A/C not meeting their TTA.

tightly related to the applied delay, as it can be observed from dotted curves. However, the average modification on flight duration is not related to the applied delay. The margins enabled by the bounded speed adjustments are not enough for compensating the applied delays. This fact could be overcome only if, first, solutions with lower absolute delays can be found (better search strategy) and, second, if the aircraft trajectory allows a bigger absolute elasticity. The latest does not depend on the solution method, but on the duration of the flight and on the number and relative position of the proximate events where it is involved.

VI. CONCLUSIONS

In this work a CP model is presented for solving the concurrence events that might happen when the departure traffic is inserted into the enroute traffic. The model has been proved in a realistic and overstressed scenario and it has been able to find suboptimal solutions in a timeframe of 180 seconds for all the performed experiments. The model constraints ensure that all the proximate events are resolved by introducing small time adjustment both on the CTOT and relevant TTO's while maximizing the adherence to the RBT's. Although the model is not able to ensure that the ATM concept of preserving the TTA in a strict time frame is met, the CP solver can find solutions that remove all the conflicts reducing the number of potential ATC interventions. The concept of preserving the TTA has been relaxed and the objective function penalizes the TTA violation. The reason for this is the limit of the trajectory elasticity, since speed adjustments are bounded to a percentage of the total RBT duration. Furthermore, the quality of the solution found so far is directly linked to the solver search strategy. In this work, default parameters for searching have been used, leading to a solution where the smallest domain values at the delay variable are tested first. The search starts with -5 minutes of adjustment on the CTOT and, due to time restriction for finding a solution, possible better solutions cannot be explored by the solver. In consequence, the obtained total delay requires extra effort for recovering the TTA and, since the trajectory elasticity is limited, no acceptable speed change can be found to meet the TTA. Further research is required to define search strategies favoring the selection of adjustments close to zero in first term. This way speed adjustment efforts are expected to be smaller.

A modeling approach for dealing with uncertainty in RBT time stamps has been also proposed. Currently, the model is under validation by using RBT and radar data obtained from DDR2 [4].

ACKNOWLEDGMENT

This research is supported by the European Union' s Horizon 2020 research and innovation program. The Project related to this research is PARTAKE "Cooperative departures for a competitive ATM network service" with Grant Agreement No. 699307. Opinions expressed in this paper reflect author's views only.

REFERENCES

[1] Amaro, M., Rudinskas, D., Barrado, C. 2015. Design of a flight management system to support four-dimensional trajectories. "Aviation", vol. 19, núm. 1, p. 58-65

[2] Javier Crespo, Cristina Cuerno, Rosa M. Arnaldo, Francisco J. Saez, Mario Sadornil, Javier Pérez and Rocio Barragán. 2014. A Comparison of the two Arrival Traffic Synchronization Concepts Envisioned for Nextgen and Sesar. 29th Congress of International Council of the Aeronautical Sciences. St. Petesburg. Russia. September 7-12, 2014.

[3] EUROCONTROL. 2016. "Flight Planning." Available from: http://www.eurocontrol.int/articles/flight-planning. [accessed 15th June 2016]

[4] EUROCONTROL, "DDR - Strategic traffic forecast," [Online]. Available: https://www.eurocontrol.int/articles/ddr-strategic-traffic-forecast. [Accessed 1 11 2016].

[5] P. Flener, J.Pearson, M. Agren, C. Garcia Avello, M. C¸ Çeliktin, and S. Dissing. 2007. "Air-traffic complexity resolution in multi-sector planning using constraint programming." Proceedings of ATM'07, the 7th USA/Europe R&D Seminar on Air Traffic Management. Barcelona, Spain

[6] IBM. 2015. IBM ILOG CPLEX Optimization Studio OPL Language User's Manual.

[7] Johnson, Sally C and Barmore, Bryan E. 2016. NextGen Far-Term Concept Exploration for Integrated Gate-to-Gate Trajectory-Based Operations. 2016 AIAA Aviation Technology, Integration, and Operations Conference; 16th ; 13-17 Jun. 2016; Washington, DC; United States.

[8] P. van Leeuwen, H.H. Hesselink and J.H.T. Rohling. 2002. Scheduling aircraft using constraint satisfaction. National Aerospace Laboratory NLR. The Netherlands. Available from: http://reports.nlr.nl/xmlui/bitstream/handle/10921/691/TP-2002-299.pdf?sequence=1. [Accessed 1 11 2016].

[9] Marriot, Kimbal and Stuckey, Peter. 1998. "Programming with Constraints". The MIT press.

[10] Mohleji, S. C. 1989. Optimal flight management system utilization with ATC automation, IEEE Aeropostale and Electronic Systems Magazine 4(2): 26–32.

[11] Nicolas Barnier, Cyril Allignol. Trajectory deconfliction with constraint programming. Knowledge Engineering Review, Cambridge University Press (CUP), 2012, 27 (3), pp 291-307. <10.1017/S0269888912000227>.<hal-00935206>

[12] Nosedal, Jenaro, Miquel A. Piera, Sergio Ruiz, and Alvaro Nosedal. 2014. "An Efficient Algorithm for Smoothing Airspace Congestion by Fine-Tuning Take-off Times." Transportation Research Part C: Emerging Technologies 44. Elsevier Ltd: 171–84. doi:10.1016/j.trc.2014.03.017.

[13] Nosedal, Jenaro, Miquel A. Piera, Adriano O. Solis, and Carles Ferrer. 2015. "An Optimization Model to Fit Airspace Demand Considering a Spatio-Temporal Analysis of Airspace Capacity." Transportation

Research Part C: Emerging Technologies 61. Elsevier Ltd: 11–28. doi:10.1016/j.trc.2015.10.011.

[14] Nosedal, Jenaro. 2016. "Aircraft departure synchronization to reduce ATC en route interventions" Available from: http://www.tdx.cat/bitstream/handle/10803/384849/jns1de1.pdf?sequence=1 [accessed on 25th June 2016]

[15] Nuic, A. Poles, D. and Mouillet V., "BADA: An Advanced Aircraft Performance Model for Present and Future ATM Systems," Int. J. Adapt. Control Signal Process., vol. 24, no. 10, pp. 850–866, 2010.

[16] Ranieri, Andrea, Rubén Martinez, Miquel Angel Piera, Javier Lopez, and Miguel Vilaplana. 2011. "STREAM – Strategic Trajectory de-Confliction to Enable Seamless Aircraft Conflict Management Concept , Methodology and Tools." Sesarinnovationdays.eu, no. December: 1–8.

[17] Tom G. Reynolds, Yan Glina, Seth Troxel and Michael McPartland. 2012. Establishing Wind Information Needs for Four Dimensional Trajectory-Based Operations. 1st International Conference on Interdisciplinary Science for Innovative Air Traffic Management (ISIATM 2012)

[18] SESAR JU. 2015. " THE ROADMAP FOR DELIVERING HIGH PERFORMING AVIATION FOR EUROPE European ATM Master Plan" Edition 2015. Available from: http://ec.europa.eu/transport/modes/air/sesar/doc/eu-atm-master-plan-2015.pdf [accessed 20th June 2016]

[19] Van Beek, Peter. 2006. "Chapter 4 Backtracking Search Algorithms." In Handbook of Constraint Programming, 2:85–134. Elsevier B.V. doi:10.1016/S1574-6526(06)80008-8.

VII. AUTHOR BIBLIOGRAPHY

Dr. Juan J. Ramos is a researcher focusing on modelling, simulation and optimization of dynamic systems, especially in the field of logistics. He received his Ph.D. from the Universitat Autonoma de Barcelona (UAB), Spain in 2003, where he is professor at the Dep. of Telecommunication and System Engineering. He is currently the program Director of the European Master on Logistics and Supply Chain Management at UAB. He is a member of LogiSim, a recognized research group on Modeling and Simulation of Complex Systems. Furthermore, he is expert in production technologies/logistics, intelligent transport systems, information and communication technology, industrial collaboration and technology transfer. He is co-founder of Aslogic.

Pau Folch received his bachelor degree in pure mathematics from the Universitat Autonoma de Barcelona (UAB), Spain in 2016. He is employee at Aslogic, working in machine learning and deep learning techniques in the ATM context. Currently, his is doing a master degree in Modelling for Science and Engineering from the (UAB).

Nina Rebecca Schefers received her bachelor degree in international information management from the Universität Hildesheim, Germany in 2013 and her master degree in Logistics and Supply Chain Management from the Universitat Autonoma de Barcelona (UAB), Spain in 2015. Currently, she is a Ph.D candidate at UAB with research work related to aeronautics and logistics. Her research subject is related to decision making and optimization of processes in Logistics, Manufacturing and Transportation.

Marko Radanovic is a PhD candidate within the Department of Telecommunications and Systems Engineering at Universitat Autònoma de Barcelona. He graduated from the University of Belgrade in Air Transport and Traffic Engineering (2007), and obtained master degree in Satellite Navigation from Politecnico di Torino (2012). His research lines are Automation in Air Traffic Management, Modelling and Simulation of Aeronautical Systems and Air Traffic Safety.

Dr. Miquel Angel Piera Eroles is full time professor in the Telecommunication and System Engineering department at Universitat Autònoma de Barcelona. Miquel graduated with excellence from UAB in Computer Engineering (1988), MSc from University of Manchester Institute of Science and Technology in Control Engineering (1991), and PhD from UAB in 1993. Dr. Piera is UAB delegate for Technical Innovation Cluster, former deputy director of the UAB Engineering School and director of LogiSim (research group on Modelling and Simulation of Complex Systems). At present Dr. Piera is active in the innovation sector, contributing as scientific advisor to the company Aslogic.

Chapter 8

8. Paper 4

The paper “A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures” which has been accepted by the journal Transportation Research Part C shows the complete detection, filtering and mitigation methodology. In comparison to paper 2, the detection and filtering methodology has been further improved by smoothing the process to obtain a powerful detection mechanism. Furthermore, the mitigation model has been improved by introducing different flight levels to the model and speed changes and by considering time uncertainty. The work shows a model that explains how to deal with the trajectory prediction under time uncertainty in the RBT and shows its results on a realistic traffic scenario obtained from obtained from Eurocontrol Demand Data Repository (DDR2). The research goal of this paper is to present a new CP mechanism to reduce the probability of separation minima infringement at the tactical level while preserving ATFM planned operations, taking into consideration time uncertainties and different flight levels. CP has been used to develop a constrained version of the ATM problem, allowing to separate the model formulation from the data and from the search strategy. The novelty of this efficient departure synchronization methodology that serves as a mitigation mechanism for concurrence events is that it considers the downstream effects of the applied measures while considering small departure adjustments, multi-flight levels, speed changes and time uncertainty.

A Constraint Programming Model with Time Uncertainty for Cooperative Flight Departures

Nina Schefers (1), Juan José Ramos González (2), Pau Folch (3) , José Luis Munoz-Gamarra(4)

(1)(2) Technical Innovation Cluster on Aeronautical Management, Universitat Autonoma de Barcelona, Sabadell (Barcelona), Spain.
(e-mail: ninarebecca.schefers@uab.es), (e-mail: JuanJose.Ramos@uab.es).
(3)(4) Department of Research and Innovation, Aslogic, Rubí, Spain
(e-mail: pfolch@aslogic.es), (e-mail: jlmunoz@aslogic.es).

Abstract— **The lack of a proper integration of strategic Air Traffic Management decision support tools with tactical Air Traffic Control interventions usually generates a negative impact on the Reference Business Trajectory adherence, and in consequence affects the potential of the Trajectory-Based Operations framework. In this paper, a new mechanism relaying on Reference Business Trajectories as a source of data to reduce the amount of Air Traffic Controller interventions at the tactical level while preserving Air Traffic Flow Management planned operations is presented. Artificial Intelligence can enable Constraint Programming as it is a powerful paradigm for solving complex, combinatorial search problems. The proposed methodology takes advantage of Constraint Programming and fosters adherence of Airspace User's trajectory preferences by identifying tight interdependencies between trajectories and introducing a new mechanism to improve the aircraft separation at concurrence events considering time uncertainty. The underlying philosophy is to capitalize present degrees of freedom between layered Air Traffic Management planning tools, when sequencing departures at the airports by considering the benefits of small time stamp changes in the assigned Calculated Take-Off Time departures and to enhance Trajectory-Based Operations concepts.**

Keywords— **Air Traffic Management; Trajectory Based Operations; Decision Support Tool; Constraint Programming; Trajectory Prediction; Uncertainties; Predictive Analysis; Conflict Detection and Resolution; Artificial Intelligence, Data Analysis; Air Transportation Planning; System-level Simulation; Reference Business Trajectories;**

1. INTRODUCTION

Air transport is an integral part of transport infrastructure and a significant sector of the economy, predicted with steady growth in the next decades. The growth will put pressure on the infrastructure that is already struggling to cope with the demand (IATA, 2017) and reduce the robustness to external conditions such as weather. Therefore, the identification and improvement of operational and managing policies for better performance of the existing airspace procedures is essential for the air traffic industry. To tackle this challenge, the initiatives Next Generation Air Transportation System (NextGen) in America and the Single European Sky ATM Research (SESAR) in Europe were established. In Europe, the Air Traffic Management (ATM) Master Plan was introduced to summarize essential operational and technological changes to deliver the essential contributions for the Single European Sky performance objectives (Sesar, 2015). To enable maximum performance gains, researchers investigate a variety of research fields such as: Separation Management, Data Science in ATM, Information Management in ATM, ATM Performance and Trajectory-based Operations (TBO). Under the framework of the TBO concept, the intention of this innovative approach is to design a competitive ATM system supporting up to a certain extent the Airspace User (AU) demands at the right time (i.e. departure slots), at the right cost (i.e. suitable level of Air Traffic Control (ATC) service) at the right place (i.e. AU's preferred trajectories) and at the right service quality (i.e. safety) without extra investments, just by removing the ATM non-added-value operations that indirectly impact on the present ATM capacity.

By empowering the concept of TBO as a flexible synchronization mechanism towards an efficient and competitive ATM service a precise description of an aircraft trajectory in space and time can be retrieved that consist of only small uncertainties, as stated in the EUROCONTROL ATM Lexicon (Eurocontrol, 2017c). Under the TBO approach, AU should fly precise 4-dimensional trajectories (4DTs), previously agreed upon with the Network Manager. Reference Business Trajectories (RBT) provide an excellent source of information to identify future situations in which two or more aircraft could require ATC directives to maintain the required separation minima. The presented approach aims to improve the present demand and capacity balance in ATM by introducing small ground delays in the programmed departure that will not affect the planned traffic since the slot time window assigned to each aircraft will be preserved. Furthermore, this integrated approach proposes mitigation methods that can consider the preferences of Airlines and Airports. The major challenge in this work is to reduce the probability of ATC tactical interventions. Therefore, the research goal of this paper is to present a new Constraint Programming mechanism to reduce the amount of ATC interventions at the tactical level while preserving Air Traffic Flow Management (ATFM) planned operations taking into consideration time uncertainties and different flight levels.

The paper is innovative in the sense it proposes an integrated approach combining potential conflict detection, and a mitigation mechanism considering trajectory prediction under time uncertainty. The work presents a set of tools to determine small Calculated Take-Off Time (CTOT) adjustments within the $[-5,10]$ minute interval along with bounded modifications on the flight duration as control actions. These actions will be calculated to mitigate the potential tight trajectory interdependencies on a multi-flight level that can emerge after inserting the traffic ready to depart.

To address the complex air transportation planning problem, the use of Constraint Programming (CP) by ILOG (Marriott and Stuckey, 1998; Van Beek, 2006; IBM, 2015) is proposed to calculate those feasible departure configurations. To develop machines that can perform higher order cognitive tasks, Artificial Intelligence techniques can enable CP as it is an emergent software technology for declarative description and effective solving of large, particularly combinatorial, problems especially involving scheduling, resource allocation, placement and planning. Finally, a novel approach that considers the time uncertainties for mitigating tight trajectories is presented. The results of the paper demonstrate how the time uncertainties are respected during the conflict mitigation phase based on CP. The modules are tested on a realistic traffic scenario.

A holistic view of the main concept is illustrated in Figure 1. The figure shows potential concurrence events, representing a potential conflict, that are detected by analysing the spatiotemporal interdependencies between flights sharing the same airspace. To mitigate the concurrence events, the trajectories are shifted using slight CTOT modifications and bounded speed adjustments in such a way that a clearance is achieved.

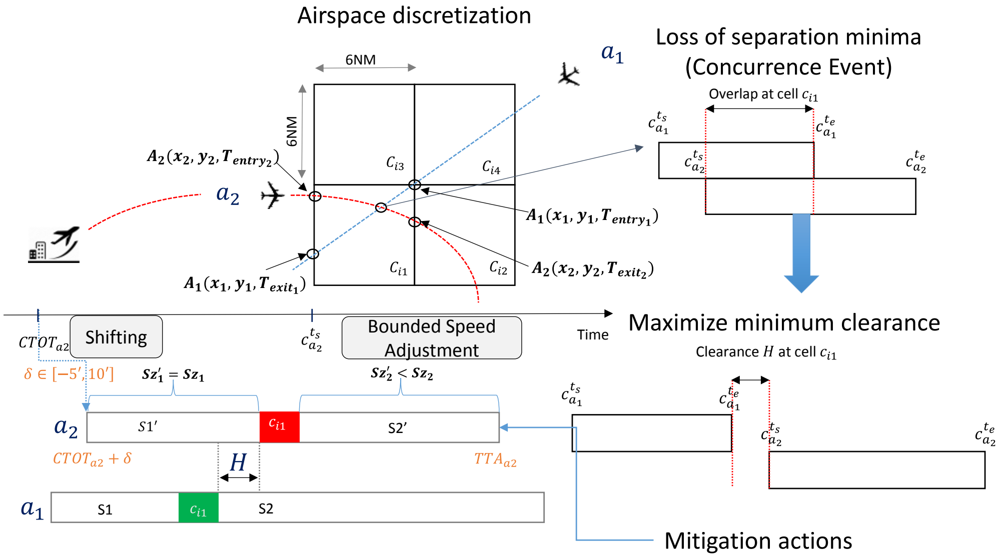


Figure 1: Overview of the proposed concept

The paper is organized as follows: Section II describes the current state of the art. Section III briefly introduces the mapping and filtering mechanism implemented to detect the trajectory interdependencies between airborne flights and the new traffic; Section IV describes the CP model proposed to mitigate the detected concurrence events that would require ATC interventions; Section V proposes a model to deal with the trajectory prediction under time uncertainty in the RBT; Section VI discusses the experimental results achieved so far; finally, conclusions and open questions for further research are discussed in Section VII.

2. STATE OF THE ART

The research sector of Conflict Detection and Resolution has undergone a paradigm shift from tactical to strategic ATC with the introduction of the 4D-TBO concept, representing the current state of the art of this research sector. Instead of adjusting flights just in time, the overall flight performance can be improved significantly by performing more efficient avoidance manoeuvres assuming proper forecasts (Kuenz, 2015). The benefit of the TBO concept is an accurate 4-dimensional trajectory (3 spatial dimensions and time) the aircraft will fly. The details of the trajectory will be shared by all involved parties through System Wide Information Management (SWIM). Also, intervention in the trajectory will happen in full knowledge of the downstream effects as shown in (Nosedal *et al.*, 2015) and hence it will be possible to pick the option causing the minimum amount of trajectory distortion. Finally, the removal of most uncertainties around the trajectory, using Artificial Intelligence (AI) and Data Analytics (DA) such as predictive analytics, makes it possible to improve the airspace volume as stated in (Wilco, 2017).

Researchers have used the advantages of the 4D-TBO concept and studied, among other, conflict detection and separation observance approaches as in (Ruiz, Piera and Del Pozo, 2013; Ruiz *et al.*, 2014) or strategic trajectory planning approaches with uncertainty as in (Chaimatanan, Delahaye and Mongeau, 2018). Efficient High Performance Conflict Detection and Resolution methods have been developed in (Kuenz, 2015) for large traffic scenarios based on an N-dimensional bisection of airspace allowing a significant reduction of complexity using the TBO concept. An initial potential conflict detection approach based on the partitioning of the airspace has been proposed by (Nosedal *et al.*, 2014), which serves as the baseline for the present work. The work presented in this article introduces major contributions both in detection and mitigation mechanisms with respect to the methods proposed in (Nosedal *et al.*, 2014). As to detection mechanisms these contributions can be summarized as follows: a 3D cell-grid based method is introduced for the 4D trajectory digitalization and an intelligent pairwise analysis is implemented to avoid false negatives in the detection of the traffic through each neighbouring cell. The proposed 3D discretization enables the representation of the trajectories from departure to arrival. From the methodological perspective, full 4D trajectories are processed and the analysis is not limited to a particular phase of the flights; from the applicability perspective, the proposed technique extends its usability to TMA and not just to en-route traffic; from the practicality perspective, the technical implementation of mapping and detection processes scales to different operational contexts, with different criteria for vertical and lateral separation. Regarding the mitigation mechanisms, the model has been totally reformulated while preserving the basic idea of the CTOT shifting to remove conflicts. In summary, the Constraint Programming (CP) model presented in this paper has the following major improvements: the new decision variables represent the whole flight trajectory, which enables the removal of its potential conflicts happening at different flight levels; introduces slight speed adjustments as decision variables in order to minimize the impact of the CTOT shifting in the arrival time; the model can tackle the effect of along-track deviations, if they can be measured or estimated; finally, the new CP formulation takes advantage from propagation mechanisms of constraints such as no overlap, span and synchronize, with a very positive impact in the computational effort required to solve this combinatorial optimization problem.

Moreover, the trajectory optimization studies focusing on the sensitivity of operational costs and efficiency have been carried out in (Vilardaga and Prats, 2015) and a coordinated multi-aircraft 4D trajectories planning, considering the buffer safety distance and fuel consumption optimization has been studied in (Qian *et al.*, 2017). Finally, machine learning techniques have been used recently, for example to address the short-term trajectory prediction problem in Terminal Manoeuvring Area (TMA) based on 4D trajectory prediction as in (Wang, Liang and Delahaye, 2017).

The introduction of the 4D TBO concept, furthermore allows introducing further system-level policy decision making processes such as Short-Term ATFCM Measures (STAM). STAM can involve measures like advancing or delaying aircraft by using the minor departure adjustments on the ground (referred to as *green delays* in (Castelli, Pesenti and Ranieri, 2011; Piera *et al.*, 2014)), fight level capping, minor re-routings e.g. in (Adacher, Flamini and Romano, 2017), linear holding e.g. in (Xu and Prats, 2017), slot allocation and sequencing methods, e.g. in (Çinar and Demirel, 2017; Liang, Delahaye and Maréchal, 2017; Marcella *et al.*, 2017), headings or speed variations which apply to a limited number of flights to reduce the complexity of the anticipated traffic peaks (Eurocontrol, 2017b). However, some manoeuvres are often not considered desirable measures by AUs due to high operational and fuel consumption costs as it was evaluated in studies of (Ferguson *et al.*, 2013; Envisa, 2017). Green delays on the ground are therefore a more acceptable alternative which is also the mitigation measure used in this work. The concept considers the small departure time adjustments recognizing global trajectory interdependencies. The goal of STAM applications is to support the dynamic Demand Capacity Balancing (DCB) concept and therefore, to improve Air Traffic Flow and Capacity Management to enhance the ATC workload as proposed in (Masalonis, Callaham and Wanke, 2003; Netjasov, Janić and Tošić, 2011).

Nowadays, the systems strongly rely on AI and DA. During the last years, supported by the introduction of the 4D-TBO concept, the application and improvement of Decision Support Tools (DST) in ATM was advanced to support the global performance ambitions for air traffic planning and optimization. From an operational research perspective, some ATM problems can be seen as decision-making problems whose resolution consists of determining the domain values of the decision variables to reach feasible solutions. Furthermore, in case an objective function is formulated to describe the benefits of each feasible solution, there are some methods that could be applied to identify the best solution. However, since ATM problems (such as re-routing, flight-level changes, or ground-holding schemes) are usually complex problems of a large dimension, and highly combinatorial, there are few AI problem-solving technologies that can cope with that many different degrees of freedom. One efficient technique is CP, which has also been used in this work to determine which aircraft CTOT should be modified within the domain of [-5,10] minutes. CP is a powerful paradigm for representing and solving a wide range of combinatorial problems (Rossi, Van Beek and Walsh, 2006) and offers a constrained version of real world data analysis problems (Rossi and Saraswat, 2006). In the last years, the paradigm has attracted much attention among researchers because it proposes on the one hand the modelling, using a high-level programming language, and on the other hand the solving, using various techniques from different areas such as mathematics, artificial intelligence, and operations research (Van Hentenryck, Simonis and Dincbas, 1992). Moreover, the nature of CP provides other important advantages such as a fast program development, an economic program maintenance and an efficient runtime performance.

Other than metaheuristic or heuristic method, such as evolutionary algorithms, CP is used to solve complex combinatorial Constraint Satisfaction Problems (CSP). CSPs are expressed in terms of three entities: variables, their corresponding domains, and constraints relating them. Constraints can be considered as the main characteristics of CP. They are treated as logical relations among several unknowns (or variables), each taking a value from a set of accepted values called domain, which can be a range with lower and upper bounds or a discrete list of numbers. Solving a CSP consists in assigning a value to each variable in such a way that every constraint is satisfied. The main interest of such a technology is the generality in the notion of what is a constraint. It enables the user to have access to a rich, high-level language that helps combine constraints together to build new ones, thus leading to an expression of the problem that is very close to its mathematical formalisation. The representation of the problem, in terms of constraints, results in short and simple programs easily adaptable to future changing requirements (Bessiere, 2006).

The application of CP is used both in scientific and industrial sectors for many kinds of application, such as scheduling or resource assignment problems. Furthermore, it has been successfully used in many research studies in the ATM field, as reported in (Allignol *et al.*, 2012). A CP model in the ATM context that would consider all degrees of freedom (3D geometry and time) to generate an optimal set of conflict-free 4D trajectories at a continental scale is out of scope reach for the current combinatorial problem-solving technologies. In this work, the use of CP to reduce the ATC interventions by profiting of time stamps (i.e. RBTs) as a degree of freedom is proposed. Furthermore, the degree of freedom is constrained to a time window of -5 to +10 minutes of the assigned departure time and, in comparison to existing works, this approach considers a fixed part which is determined by those aircraft that are already in the air and cannot be modified. Therefore, the large-scale space of solutions is reduced to a size in which CP models could provide feasible and even quasi-optimal solutions.

Considering the ATM sources of uncertainty (parameters of aircraft models in trajectory prediction, weather, failure of ATC systems, cancellation of flights, etc.) and the degree of safety, a rolling horizon model scope is recommended to be considered in CP models to handle reasonable amounts of uncertainty. To avoid being affected by the scalability problems, the time windows should be considered small enough to take into account only a limited amount of uncertainty. Based on the classification of uncertainty sources as described in (Mondoloni, 2006; Casado, Goodchild and Vilaplana, 2012) in which many uncertainties can be modelled as stochastic variables, (Pabst *et al.*, 2013) proposes a method to transfer those stochastic errors to the position errors. In this work, a similar approach is presented, focusing on the weather forecast uncertainties, particularly the impact of along-track wind uncertainty.

Existing literature shows that CP in ATM is used in rolling horizons in which the ‘past’ part of the current solution is fixed and the decision variables are considered as constants. The ‘future’ part of the problem is resolved with the new horizon. Various CP models to improve air traffic services have been developed. For example, a CP model for flight-level allocation for a vertical separation was developed in (Barnier and Brisset, 2004) and a CP model that minimizes the number of required ATFCM regulations has been developed in (Kerlirzin *et al.*, 2000). Models that focus on improving the ATC workload have been developed in (Trandac, Baptiste and Duong, 2005) where a CP model for an airspace sectorization is presented and in (Flener *et al.*, 2007) a CP model to minimize and balance the traffic complexities of airspace of the adjacent sectors is proposed. Finally, (Chemla *et al.*, 1995) laid the foundation for CP modelling of the slot allocation problems. In (Allignol *et al.*, 2012) a better description of improvements to the slot allocation problems together with CP applications can be found. Further planning methods and decision support tools can be found in (Barnier and Allignol, 2009) where a CP model for a conflict-free planning method is introduced and (Van Leeuwen, Van and Houwert, 2003) where a CP model for decision support is presented to aid the controllers in planning the movements of flights within an airport and its airspace.

The present work proposes an evolved and improved CP model based on the initial work of (Schefers *et al.*, 2016) to solve the problem by describing the trajectory as a sequence of the time intervals that represent the conflict-free segments and the concurrence events segments introducing a multi-flight level approach. The scheduling consists in ensuring of the non-concurrent use of the areas that were in conflict. Since the tools highly rely on an accuracy of the Trajectory Prediction (TP) to reduce the number of the en-route conflicts, the time uncertainty is considered in the approach and to complement it different flight levels are considered.

3. 3D CONCURRENCE EVENT DETECTION METHODOLOGY

The conflict detection is composed of two processes: the mapping process and the spatiotemporal interdependency detection. The concurrence event detection methodology is designed to detect concurrence events in different flight levels (FL). In comparison to existing concurrence event detection models, our approach does not only identify pairwise conflicts but interdependencies between trajectories that lose their safety buffer. The benefits of this methodology are the efficient way of identifying concurrence events in air, the possibility to understand the impact of the trajectory interdependencies and to apply mitigation measures.

In the following, the three processes for the 3D concurrence event detection are described.

3.1 3D Mapping Process

To detect concurrence events, the European airspace covering the longitude of -20 to 30 degrees and latitudes of 0 to 80 degrees, is partitioned into square cells of 6 NM representing the lateral separation minima en-route. The defined horizontal separation minimum based on radar and/or ADS-B and/or MLAT system according to ICAO Doc 4444 (ICAO, 2016) is set to 5 NM. In this work, the horizontal separation is set to 6 NM to take into account any lateral deviations with respect to the RBT below 1 NM. It is worth to mention that the cell size is a parameter that might be changed depending on the operational context (e.g. in TMA the cell size can be set to 3NM). Taking advantage of the 4D-TBO concept that is based on the integration of time into the 3D aircraft trajectory, 4D trajectories are project onto the grid. The benefit of working with 4D trajectories is that this concept ensures that the aircraft can fly on a practically unrestricted, optimum trajectory for as long as possible in exchange of the aircraft being obliged to meet very accurately any arrival time over a designated point (SKYbrary, 2017). As a result of the mapping projection a 4D trajectory is partitioned in segments, one for each cell the trajectory occupies. All the generated segments are stored in a matrix representing the grid, whose size depends on the cell size and vertical separation to be considered. The segments are stored as a sequence of two or more 4D points containing latitude, longitude, time and flight level. The first point in the sequence is the entry point in the cell and the last is the exit point. The concept of the airspace discretization and mapping process can be seen in Figure 2.

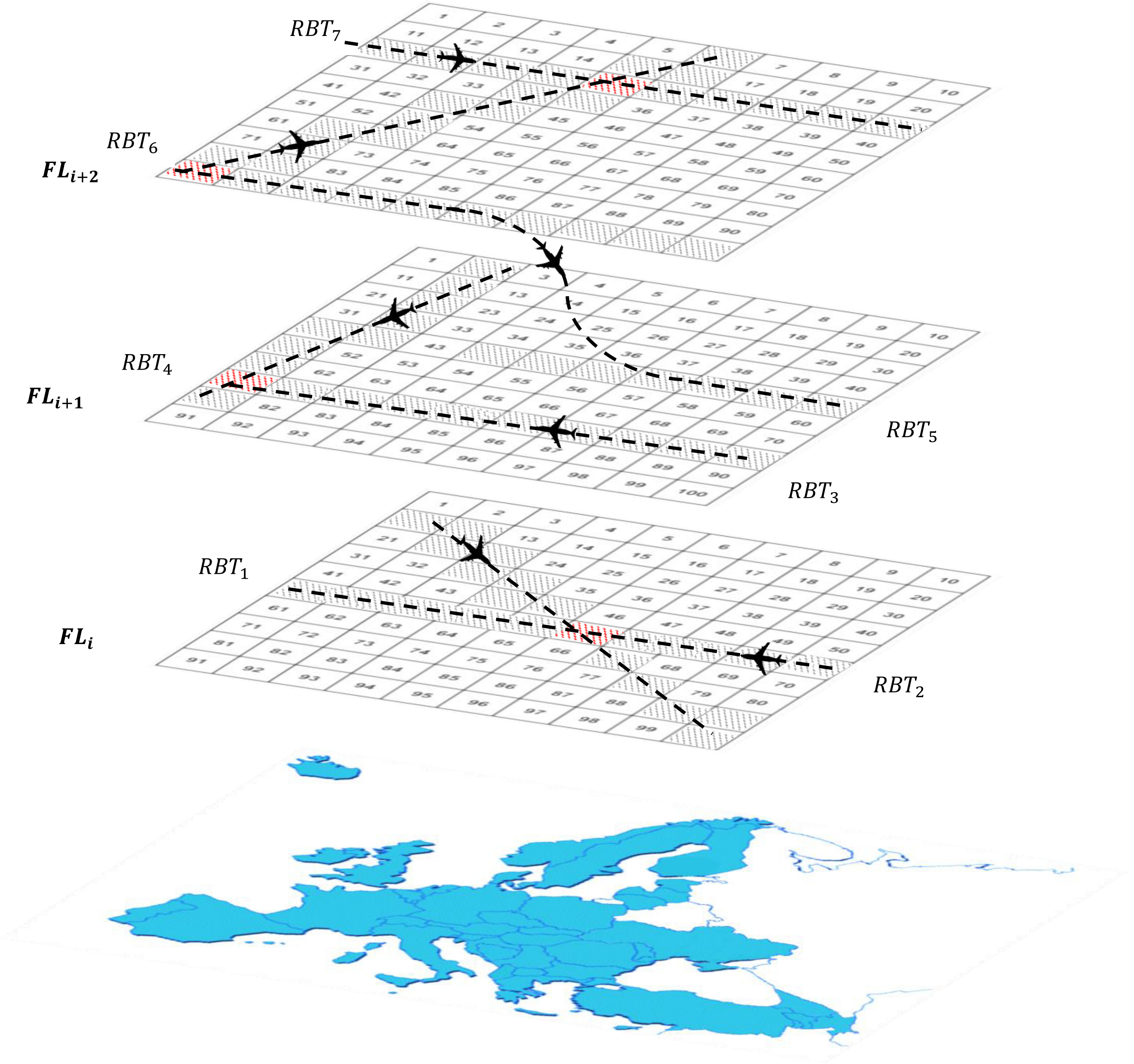


Figure 2: 3D Mapping Process

To achieve a multi-level mapping an aircraft a_i that changes its flight level from flight level FL_i to FL_{i+1}, will be represented on both flight levels during its climbing/descend manoeuvre. Applying this method, it might occur that a concurrence event for aircraft a_i is registered in several fight levels because it is actually performing a climbing or descend manoeuvre, so it might happen that several concurrence events involving the same aircraft are detected simultaneously at the different flight levels. This is a rather conservative but safe approach which is the most important factor in air traffic management. A graphical illustration of the method used to detect concurrence events on a 3D level is represented in Figure 3.

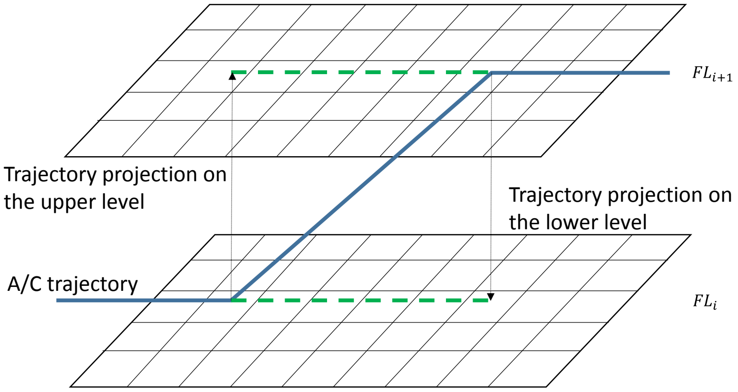


Figure 3: 3D Multi-flight level mapping

3.2 Spatio-Temporal Interdependency detection

A concurrence event occurs when two or more aircraft loss the separation minima (vertical or horizontal). The presented approach solves the existing concurrence events applying time shifts to some of the flights. However, this aircraft take-off times shifts can generate additional concurrence events, which are called potential concurrence events. Hence for the mitigation phase the potential concurrence events, that are the critical spatio-temporal interdependencies between pairs of aircraft, must be detected.

The detection of spatio-temporal interdependencies is performed by calculating the temporal looseness ("clearance time" or "overlap time") between a pair of aircraft segments in the same cell (see Figure 4). The temporal looseness H of two aircraft can be calculated by determining the minimum value of the exit time of the two aircraft minus the maximum entry time. To be considered as a potential concurrence event the temporal looseness H of a pair must satisfy:

$$H = min\left(c_{a_1}^{t_e}, c_{a_2}^{t_e}\right) - max\left(c_{a_1}^{t_s}, c_{a_2}^{t_s}\right) \geq -h_m = (\delta_M - \delta_m) \tag{1}$$

Where δ_M is the maximum slot time shifting that can be applied (e.g. 10 min), and δ_m the maximum advanced time (e.g. -5 min), $c_{a_i}^{t_s}$an refers to the time of an aircraft a_i entering into the cell and correspondingly, $c_{a_i}^{t_e}$ refers to the time of the aircraft leaving the cell c. When $H \leq 0$ there is a clearance, and when $H > 0$ there is an overlap. For instance, if the domain for rescheduling the CTOT is set to [-5, 10] minutes, the greatest value of H to consider a pair of aircraft as a potential concurrence event is 15 minutes (900 seconds). Therefore, the list of the tighter spatio-temporal interdependences must be filtered with $h_m = 15$ minutes, the maximum CTOT shifting window which would not endanger the safety separation even if the shift at each interval end is applied to each aircraft.

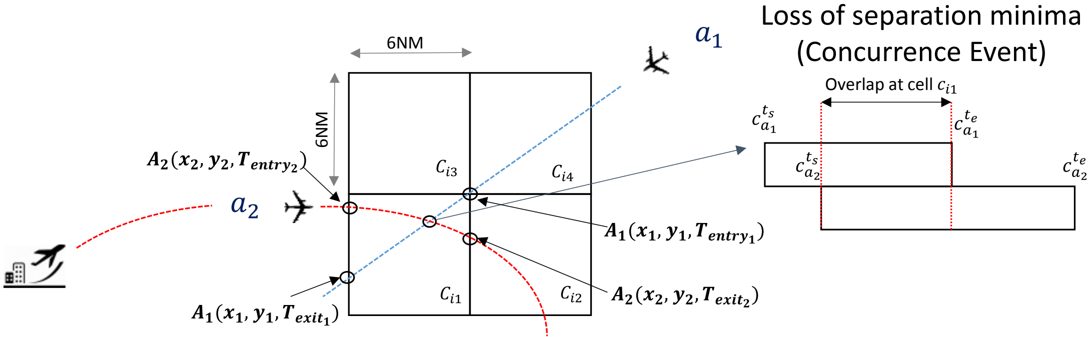


Figure 4: Spatio-temporal interdependency registration

It may happen that two or more aircraft are flying at two neighbouring cells losing the separation minima, so cell occupancy check will miss those potential concurrence events. To ensure the reliability of the potential concurrence event identification, the traffic in the surrounding cells of each cell j is analysed using an intelligent neighbourhood check in order to properly detect any loss of separation. The algorithm takes for each occupied cell j all its surrounding cells that have at least one aircraft inside. Then the H value is computed for all possible pairs of aircraft that are in cell j and in the neighbourhood, an all those pairs that have and $H > 900$ are discarded. For the rest of the pairs, the minimum distance between the segments is calculated and compared with the threshold value (6NM). The Figure 5 illustrates how this process will detect the loss of separation between Ac_1 and Ac_2 in cell j and cell i_7. This verification is performed for each occupied cell in the grid.

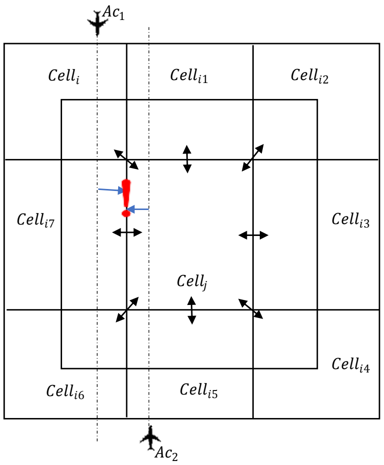


Figure 5: Neighbourhood analysis

The algorithm checks all the cells in the grid, and if the occupancy of the cell j is greater than zero then the temporal looseness is computed for all the pairs of segments inside the cell j, as well as all the possible pairs that have one segment in the cell j and its neighbouring cells. For those pairs that have one of the segments out of the cell j with $\mathrm{H} \geq -\mathrm{h_m}$, the algorithm also computes the minimum distance. Hence, the computational effort of the algorithm depends on the grid size (number of cells) and, more relevant, on the distribution of the trajectory segments in the grid, since the combinatorial part of the algorithm appears in the neighbourhood pairwise analysis when all the possible pairs are checked. Nevertheless, computational times are very competitive when analysing realistic, or even stressed, traffic (few seconds in a standard desktop computer as discussed later in this paper). This is because it doesn't make sense to decrease the cell size arbitrarily and also because of the traffic density in a given area is limited by the ATM capacity, so the pairwise analysis doesn't create any combinatorial explosion. Furthermore, the proposed algorithms can be easily parallelized in order to make neglectable the detection computational time in any practical application.

4. MITIGATION PROCESS

The conflict mitigation process is modelled as an optimization problem in Constraint Programming (CP) formalism (Marriott and Stuckey, 1998). The presented approach adopts CP as the solving technique for concurrence event mitigation recognizing the synchronization problem as a scheduling problem, similar to some extent to the well-known Job Shop Scheduling Problem (JSSP) or for the Single Objective Optimization Constrained Scheduling Problem (SOCSP) (Tselios, Savvas and Kechadi, 2013). Roughly, this problem consists in allocating the proper resources to the list of jobs facing an optimization goal to minimize temporal, productivity or efficiency cost functions. Like the JSSP or the SOCSP, the available cells, as portions of the airspace, can be considered as the existing resource and the aircraft as the jobs that are performed requiring the resource.

The objective function of the problem is to reschedule the CTOT of an aircraft on the ground in such a way that en-route concurrence events are minimized while the AU preferred RBT is preserved and the domain is respected. The domain of the here presented approach is the allowed green delay time slot shifting of the CTOT of [-5,10] minutes. To reach this goal, the problem model considers concurrence events at different flight levels, along-track deviations, bounded modifications on the flight duration to meet the Target Time of Arrival (TTA), and small departure adjustments within the [-5,10] CTOT interval.

4.1 Tight trajectory interdependencies resolution

The output of the 3D concurrence event detection process includes a list of all concurrence events that have been detected during a specific time within a specific airspace volume. This data serves as the input for the mitigation process. To remove all concurrence events the trajectory resolution is modelled using two control actions: shifting the entire trajectory according to the slot time shifting that has been applied to the CTOT, applying small speed adjustments meeting the TTA. Furthermore, the model considers the resolution of concurrence events at different flight levels and considers time uncertainties to create a more realistic scenario. The parameters for the model are declared as follows.

Let A be the set of aircraft, F the set of Flight Levels (FL) and C the set of cells with concurrence events and $c_a^f =< c, a, f >$ the pairing between the aircraft a using a given cell c at a given FL. The pairings $c_a^f \in C_A^F$ are defined as:

$$C_A^F = \{< c, a, f > \mid \forall c \in C, \forall a \in A, \forall f \in F\}$$

the time occupancy of the cell c by aircraft a at a given FL is defined by the two parameters:

$$\begin{aligned} c_{a_f}^{ts} &\equiv entry\ time \\ c_{a_f}^{te} &\equiv exit\ time \end{aligned} \tag{2}$$

To meet the agreed TTA, the model also needs to consider small speed adjustments. Shifting the whole trajectory according to the applied slot time shifting would not allow to meet the TTA. Therefore, data structures are introduced to model trajectory segments for speed adjustments. The condition for applying speed adjustment is that the segments are of a certain minimum duration to allow the efficient resolution of the conflicts and to ensure a reasonable operation of the aircraft in terms of fuel consumption.

Let $\hat{g}_i^{a_f}$ be a segment of the aircraft a trajectory at a given FL. Therefore, the RBT can be noted as:

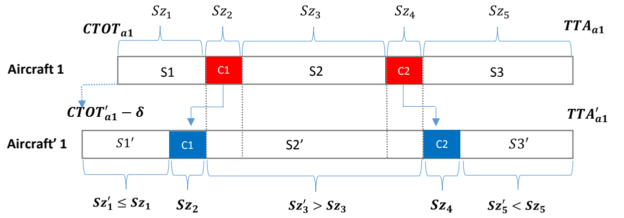
$$RBT_a = \{\hat{g}_i^{a_f}\}, \qquad i = 1..p(a)$$

where $p(\cdot)$ is the number of segments required for describing the trajectory. For instance, Figure 6 shows the trajectory segments of an aircraft a_1, represented as $RBT_a = \{S1, C_1, S2, C_2, S3\}$ with

$$s(\hat{g}_i^{a_f}) = \text{start time of } \hat{g}_i^{a_f}, \qquad (3)$$

$$\mathrm{e}(\hat{g}_i^{a_f}) = \text{end time of } \hat{g}_i^{a_f}$$

where the functions $s(\cdot)$ and $e(\cdot)$ yield the start and end times of the corresponding RBT segments. Finally, the concept of segment elasticity defined by the function $l(\hat{g}_i^{a_f})$ is introduced to denote the allowed speed variation as a percentage of the $\hat{g}_i^{a_f}$ segment duration $sz(\hat{g}_i^{a_f})$. The model of the RBT segments, the CTOT shifting process and the speed adjustments are illustrated in Figure 6.



$$RBT_a = \{\hat{g}_1^{a_f}, \hat{g}_2^{a_f}, \hat{g}_3^{a_f}, \hat{g}_4^{a_f}, \hat{g}_5^{a_f}\} = \{S_1, C_1, S_2, C_2, S_3\}$$

$$p(a) = 5$$

$$s(\hat{g}_i^{a_f}) = \text{start time of } \hat{g}_i^{a_f},$$

$$\mathrm{e}(\hat{g}_i^{a_f}) = end\ time\ of\ \hat{g}_i^{a_f}$$

Figure 6: Graphical illustration of the tight trajectory resolution including CTOT shifting and speed adjustment and the RBT segments

4.2 Decision variables

To ensure that the departure adjustment of the aircraft remain in the domain of [-5,10] minutes, the integer decision variable δ_a is defined as the slot time shifting applied to the CTOT of aircraft a:

$$\delta_a \in [\delta_{min}, \delta_{max}], \forall a \in A \qquad (4)$$

where $\delta_{min} = -5$ and $\delta_{max} = 10$ minutes, sets the domain for the slot time shifting decision variable.

The use of a cell by an aircraft is modelled by means of interval decision variables. Interval decision variables represent time periods whose duration and position in time are unknown in the optimization problem. The interval is characterized by a start value, an end value and a size. Addressing this concept as a scheduling problem, the interval is the time during which something happens (e.g. an activity is carried out). To model the occupancy of the cell c by an aircraft a at a given FL f, the following interval decision variable is declared:

$$P_{c_{a_f}} = \left[s_{c_{a_f}}, e_{c_{a_f}}\right), \qquad \forall\, c_{a_f} \in C_{A_F}$$

with the size:

$$sz\left(P_{c_{a_f}}\right) = e_{c_{a_f}} - s_{c_{a_f}} = c_{a_f}^{te} - c_{a_f}^{ts}$$

where $s_{c_{a_f}}$ and $e_{c_{a_f}}$ are the interval start and end time respectively.

Since the shifting applied to the trajectory to avoid the concurrence events is determined by the slot time shifting δ_a and the length of the RBT segments, the domain of the interval variable can be defined as:

$$P_{c_{a_f}}: sz(P_{c_{a_f}}) = \left(c_{a_f}^{te} - c_{a_f}^{ts}\right), \forall c_{a_f} \in C_{A_F} \qquad (5)$$

Furthermore, each of the cells can be occupied only by one aircraft at a time, so the aircraft going through the cell must be sequenced accordingly, see Figure 7. The decisions on the use of conflicting cells are modelled by sequence variables to define the order of the usage, which are defined as:

$$O_c = \left\{P_{c_{a_f}} \middle| c_{a_f} \in C_{A_F}\right\}, \qquad \forall c \in C, \forall f \in F \qquad (6)$$

with the permutation π of the sequence variable O_c as the function

$$\pi: O_c \to [1, m]$$

where $m = |O_c|$ is the number of aircraft going through the cell c. The elements of the sequence variable meet the following conditions:

$$P_{c_{ai_f}} \neq P_{c_{aj_f}} \Rightarrow \pi\left(P_{c_{ai_f}}\right) \neq \pi\left(P_{c_{aj_f}}\right), \forall\, P_{c_{ai_f}}, P_{c_{aj_f}} \in O_c$$

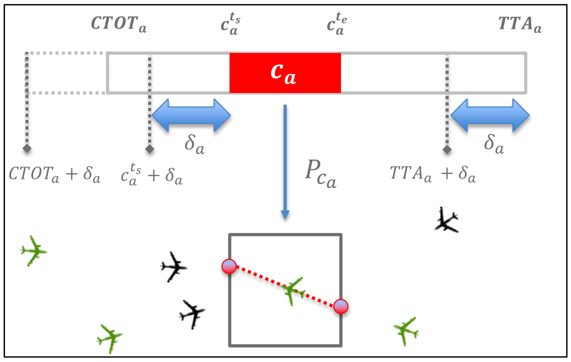


Figure 7: Illustration of the sequencing of the occupancy of the cell c by an aircraft $\boldsymbol{a}$ at a given FL $\boldsymbol{f}$ (referred to as $\boldsymbol{P}_{c_{a_f}}$) in such a way that the cells can be occupied only by one aircraft at a time.

In a second step, the segments of the RBT have to be modelled to be able to introduce speed changes which ensure that the TTA is met. In this case, the duration of the entire flight becomes an unknown itself, since the CTOT can be shifted while intending to preserve the TTA.

Therefore, a decision interval variable G_a is introduced for representing the entire flight:

$$G_a = [s_a, e_a) \tag{7}$$

where s_a will be the take-off time and e_a the arrival time in the solution.

Secondly, the interval variables representing the segments of the G_a solution trajectory are modelled. Let $g_i^{a_f}$ be the interval variable for a segment of the RBT at a given FL:

$$g_i^{a_f} = \left[s\left(g_i^{a_f}\right), e\left(g_i^{a_f}\right)\right), \forall a \in A, \forall f \in F, \forall i \in 1..p(a)$$

and the size of the $g_i^{a_f}$ segment is

$$sz\left(g_i^{a_f}\right) = e\left(g_i^{a_f}\right) - s\left(g_i^{a_f}\right)$$

The domain of the $g_i^{a_f}$ segment can be defined as:

$$sz\left(g_i^{a_f}\right) \in \left[sz\left(\hat{g}_i^{a_f}\right) - l\left(\hat{g}_i^{a_f}\right), sz\left(\hat{g}_i^{a_f}\right) + l\left(\hat{g}_i^{a_f}\right)\right] \tag{8}$$

where $l\left(\hat{g}_i^{a_f}\right)$ is the elasticity of the segment that results from bounded speed adjustments. Therefore, the interval duration can differ from the original RBT segment duration, since the bounded speed changes enable the elasticity $l\left(\hat{g}_i^{a_f}\right)$ of the segment. The domain for the interval start and end time cannot be specified, since their solution values are a combination of the take-off slot time shift and the bounded speed adjustments.

Finally, an interval decision sequence variable T_a is introduced to set the relationship between the trajectory segments $g_i^{a_f}$ and the entire trajectory G_a:

$$\begin{aligned} &T_a = \left\{g_i^{a_f} \mid \forall a \in A, \forall f \in F, i \in 1..p(a)\right\} \\ &\pi: T_a \rightarrow [1, n] \\ &g_i^{a_f} \neq g_j^{a_f} \Rightarrow \pi\left(g_i^{a_f}\right) \neq \pi\left(g_j^{a_f}\right), \forall g_i^{a_f}, g_j^{a_f} \in T_a \end{aligned} \tag{9}$$

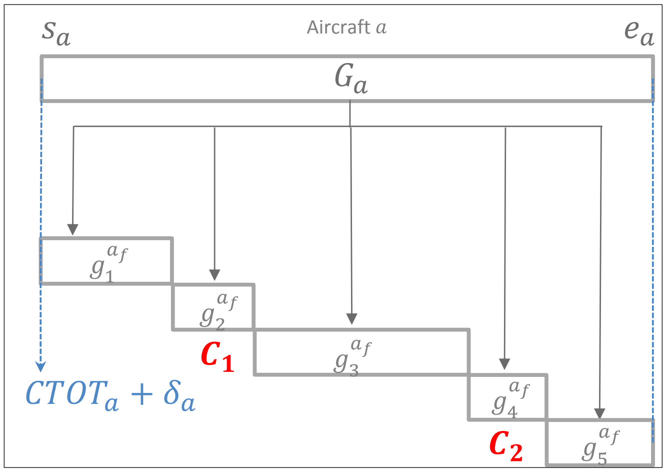


Figure 8: Graphical representation of the RBT segments and the trajectory

As it can be seen in Figure 8 an interval sequence decision variable is defined on a set of interval variables, in this case $g_i^{a_f}$. The value of an interval sequence variable represents a total ordering of the interval variables of the set. Any absent interval variables are not considered in the ordering.

4.3 Constraints

Constraints in a model represent the limit on the combinations of values for decision variables. In the following, the constraints that were identified in order to define the space of feasible solutions for this problem are described. The first constraint aims to model the shifting of every interval variable $P_{c_{a_f}}$ according to the slot time shifting:

$$s\left(P_{c_{a_f}}\right) = c_{a_f}^{te} + \delta_a, \forall c_{a_f} \in C_{A_F} \tag{10}$$

where the function $s(\cdot)$ is defined as the interval start time (aircraft entry to cell c):

$$s\left(P_{c_{a_f}}\right) = s_{c_{a_f}} \tag{11}$$

The second constraint for the interval variable $P_{c_{a_f}}$ is the no overlap constraint that imposes a set of interval variables to not overlap each other in time. In this case, all aircraft in a cell c with proximate events should have no overlap:

$$\begin{gathered} \forall P_{c_i}, P_{c_j} \in O_c \\ NO(O_c) \Leftrightarrow \pi(P_{c_i}) \leq \pi(P_{c_j}) \Rightarrow e(P_{c_i}) \leq s(P_{c_j}) \end{gathered} \tag{12}$$

where the function $e(\cdot)$ is defined as the interval end time (aircraft exit from cell c):

$$e\left(P_{c_{a_f}}\right) = e_{c_{a_f}} \tag{13}$$

and the no overlap is guaranteed for the proximate event P_{c_i} at a position prior to any P_{c_j} by constraining its end time to be lower or equal to the start time of the subsequent proximate events P_{c_j}.

The interval variable G_a which represents the duration of the flight is determined by the constraint of the take-off time (equation 14) and the time of arrival (equation 15).

$$s(G_a) = CTOT_a + \delta_a \tag{14}$$

$$e(G_a) \in [TTA_a - 1, TTA_a + 1] \tag{15}$$

TTA adherence is a main objective to enhance capacity at arrival airports and cannot be preserved by only shifting the CTOT and therefore, the full trajectory. The TTA in ATM has a small margin of [–1, 1] minute. Therefore, its compliance is of high importance. To meet these conditions, the end time $e(G_a)$ has been constrained to be in the interval $[TTA_a - 1, TTA_a + 1]$ by introducing the concept of segments for describing the full trajectory from departure (CTOT) until the arrival time to the destination (TTA).

Furthermore, the relationship between the flight interval variable and its segments is modelled by the following *span* condition to ensure the completeness of the trajectory:

$$span\left(G_a, \{g_i^{a_f}\}\right), \forall a \in A, \forall g_i^{a_f} \in T_a$$

This constraint sets the following time relationship among the interval variables:

$$\begin{cases} s(G_a) = \min\limits_{i \in [1, p(a_f)]} (\{s(g_i^{a_f})\}) \\ e(G_a) = \max\limits_{i \in [1, p(a_f)]} (\{e(g_i^{a_f})\}) \end{cases} \tag{16}$$

The constraint *span* states that the interval flight spans over all present intervals from the set segments. That is, interval flight G_a starts together with the first present segment interval and ends together with the last one.

Therefore, the following three constraints are set to order the trajectory segments:

1. The *no overlap* constraint to ensure that interval variables to not overlap each other. In this case, the individual RBT segments should have no overlap.

$$NO(G_a) \Leftrightarrow \pi(g_i^{a_f}) < \pi(g_j^{a_f}) \Rightarrow e(g_i^{a_f}) \leq s(g_j^{a_f}) \tag{17}$$

2. The constraint that one segment has to start before the next:

$$e(g_i^{a_f}) \leq s\left(g_j^{a_f}\right), \forall i, j : i < j \tag{18}$$

3. The constraint that ensures that the start of segment j takes place after the end of segment i.

$$e(g_i^{a_f}) = s\left(g_j^{a_f}\right), \forall i, j : j = i + 1 \tag{19}$$

Moreover, the $P_{c_{a_f}}$ interval variable, that is used in combination with the sequence variable O_c to remove the concurrence events at cell c, must be linked with the concurrence segments of the trajectory T_a, since they are representing the same time windows. This is accomplished by the following constraint:

$$\begin{cases} s(g_i^{a_f}) = s(P_{c_{a_f}}) \\ e(g_i^{a_f}) = e(P_{c_{a_f}}) \end{cases} \Leftrightarrow \begin{matrix} s(\hat{g}_i^{a_f}) = c_{a_f}^{t_s} \\ e(\hat{g}_i^{a_f}) = c_{a_f}^{t_e} \end{matrix}, \forall c_{a_f} \in c_{A_F} \tag{20}$$

In summary, there are two interval variables: $P_{c_{a_f}}$ that represents the occupancy of the cell c by an aircraft a at a given FL f (equation 5) and $g_i^{a_f}$ that represents the segment of the RBT at a given FL (equation 8). Both are scheduled over the pairing between the aircraft a using a given cell c at a given FL modelled as $c_a^f \in C_A^F$ (equation 2) ensuring with equation 20 that $P_{c_{a_f}}$and $g_i^{a_f}$ are linked to each other since they represent the same time window, see Figure 9.

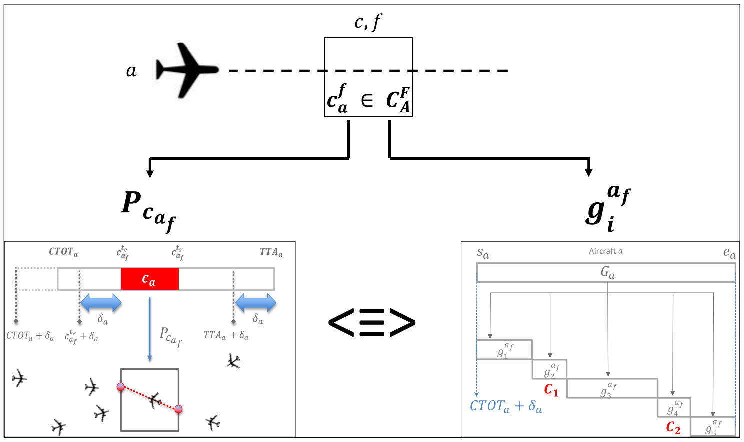


Figure 9: Graphical illustration of the use of the interval variables $\boldsymbol{P_{c_{a_f}}}$and $\boldsymbol{g_i^{a_f}}$over the paring of the aircraft, cell and FL $\boldsymbol{c_a^f} \in \boldsymbol{C_A^F}$and the linkage between both interval variables as expressed in equation 20.

Finally, the RBT segments of different FLs need to be synchronized to model the 3D concurrence event mitigation. Recalling the concurrence event detection process described in Figure 3, the RBT exists in the lower and upper flight level during the FL change of the RBT. Therefore, the synchronize constraint is used to synchronize the start and end of intervals $g_i^{a_{f_i}}$(segments of the RBT), see Figure 10. This constraint makes all present intervals in the array start and end together with interval $g_i^{a_{f_i}}$, if it is present, while remaining with just one $g_i^{a_{f_i}}$ RBT segment to form the trajectory G_a (blue striped cell $g_i^{a_{f_i}}$ in Figure 10). The constraint that ensures that the RBT is recognized in both FL is defined as follows:

$$synchronize\left([g_i^{a_{f_i}}], \left\{g_i^{a_{f_j}}\right\}\right), \forall g_i^{a_f} \in T_a \tag{21}$$

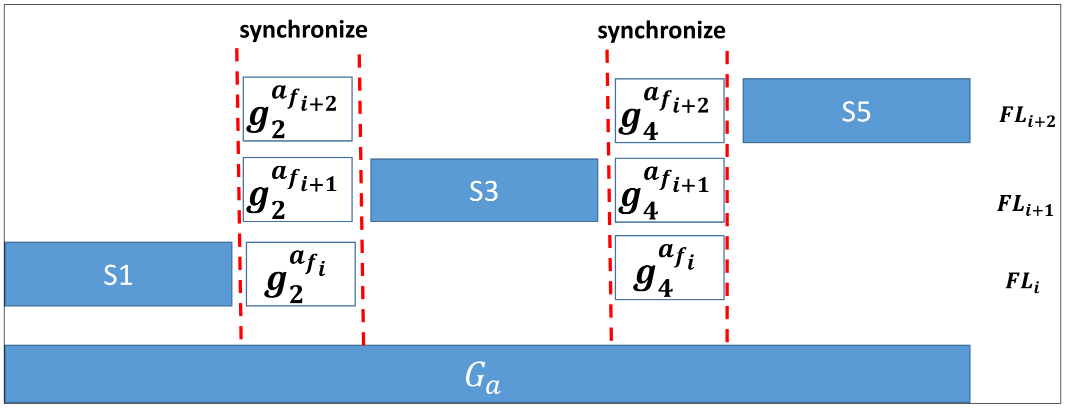


Figure 10: Flight Level synchronization

4.4 Optimization goal

The objective function is expressed in a bi-objective optimization goal with the intention to bind the TTA on one hand and to minimize the total aircraft slot time shifts on the other hand. However, it may occur that sometimes no solution can be found because time adjustment is bounded and the slot time shifting δ_a cannot be compensated by the speed adjustments. For this reason, the TTA constraint is relaxed with the following logical function:

$$L(G_a) = \begin{cases} 1, & e(G_a) \notin [TTA_a - 1,\, TTA_a + 1] \\ 0, & \text{otherwise} \end{cases}$$

The bi-objective optimization goal that combines both aspects which are w_1 that minimizes the total aircraft slot time shifts, and w_2 that binds the TTA is formulated as follows:

$$\min w_1 \sum_{a=1}^{n} |\delta_a| + w_2 \sum_{a=1}^{n} L(G_a) \tag{22}$$

where a refers to the aircraft, δ_a is the slot time shift applied and $L(G_a)$ represents the minimization of all RBT segments according to their allowed elasticity if the TTA cannot be met.

The entire optimization model is listed here:

A set of aircraft
C set of cells that have a concurrence event
F set of Flight Levels
$C_A^F = \{< c, a, f > \mid \forall c \in C, \forall a \in A, \forall f \in F\}$
$RBT_a = \{\hat{g}_i^{a_f}\}, \qquad i = 1..p(a)$
d.v. $\delta_a \in [\delta_{min}, \delta_{max}], \forall a \in A$
d.v. $P_{c_{a_f}}: sz(P_{c_{a_f}}) = \left(c_{a_f}^{te} - c_{a_f}^{ts}\right), \forall c_{a_f} \in C_{A_F}$
d.v. $O_c = \left\{P_{c_{a_f}} \middle| c_{a_f} \in C_{A_F}\right\}, \ \forall c \in C, \forall f \in F$
d.v. $G_a = [s_a, e_a)$
d.v. $g_i^{a_f} = \left[s(g_i^{a_f}), e(g_i^{a_f})\right), \forall a \in A, \forall f \in F, \forall i \in 1..p(a)$:
$\qquad sz(g_i^{a_f}) \in [sz(\hat{g}_i^{a_f}) - l(\hat{g}_i^{a_f}), sz(\hat{g}_i^{a_f}) + l(\hat{g}_i^{a_f})]$
d.v. $T_a = \{g_i^{a_f} \mid \forall a \in A, \forall f \in F, i \in 1..p(a)\}$

minimize
$w_1 \sum_{a=1}^{n} |\delta_a| + w_2 \sum_{a=1}^{n} L(G_a)$
subject to {
$s\left(P_{c_{a_f}}\right) = c_{a_f}^{te} + \delta_a$
$\forall P_{c_i}, P_{c_j} \in O_c$
$\qquad NO(O_c) \Leftrightarrow \pi(P_{c_i}) < \pi(P_{c_j}) \Rightarrow e(P_{c_i}) \leq s(P_{c_j})$
$s(G_a) = CTOT_a + \delta_a$
$e(G_a) \in [TTA_a - 1, TTA_a + 1]$
$span(G_a, \{g_i^{a_f}\}), \forall a \in A, \forall g_i^{a_f} \in T_a$
$\forall a \in A, \forall f \in F, \forall i, j \in 1..p(a)$
$\qquad NO(G_a) \Leftrightarrow \pi(g_i^{a_f}) < \pi(g_j^{a_f}) \Rightarrow e(g_i^{a_f}) \leq s(g_j^{a_f})$

$$e\left(g_i^{a_f}\right) \leq s\left(g_j^{a_f}\right), \forall i, j: i < j$$
$$e\left(g_i^{a_f}\right) = s\left(g_j^{a_f}\right), \forall i, j: j = i + 1$$
$$\begin{cases} s\left(g_i^{a_f}\right) = s(P_{c_{a_f}}) \\ e\left(g_i^{a_f}\right) = e(P_{c_{a_f}}) \end{cases} \Leftrightarrow \begin{matrix} s\left(\hat{g}_i^{a_f}\right) = c_{a_f}^{t_s} \\ e\left(\hat{g}_i^{a_f}\right) = c_{a_f}^{t_e} \end{matrix}, \forall c_{a_f} \in c_{A_F}$$
$$synchronize\left([g_i^{a_{f_i}}], \left\{g_i^{a_{f_j}}\right\}\right), \forall g_i^{a_f} \in T_a$$
}

5. DEALING WITH UNCERTAINTIES

Considering the ATM sources of uncertainty (parameters of aircraft models in trajectory prediction, weather, delays, cancellation of flights, etc.) and the degree of safety required in air traffic management, a rolling horizon model scope should be considered to handle reasonable amounts of uncertainty.

The Flight Management System (FMS) provides the primary navigation, flight planning, optimized route determination and en-route guidance for the aircraft. The guidance function of the FMS ensures that an aircraft within the TBO concept will fly its RBT. But some deviations may occur both in time and space as a consequence of the previously mentioned causes. The time uncertainty is defined as the inability to exactly determine in which instance of time an aircraft will overfly a certain fixed spot in the space.

The space uncertainty, which would be defined in the same way, shall not be taken into account since it is solved with the space discretization done by the conflict detection procedure described above. The methodology considers the effects on potential conflicts due to lateral deviations from RBT to be absorbed by the size of the cells (6 NM), and vertical deviations in climbing or descend phases to be absorbed by the projecting of the trajectory to the upper on lower flight level grid. That is, any deviation below 1 NM will result in the same conflicts detected at the detection process.

However, time differences between the en-route flights with respect to their corresponding RBT can affect the time window occupancy of the cells in conflict as defined in equation 2, so that the action to be taken for mitigating the potential conflicts can be affected, too.

More formally, let $\gamma(t) \in \mathbb{R}^3$ be the RBT and $\bar{\gamma}(t) \in \mathbb{R}^3$ the actual flown trajectory. Then, under the TBO concept we will expect that $\|\gamma(t) - \bar{\gamma}(t)\|_2 \approx 0$ at least in most cases. If in any of the verifications of the actual state of airborne flights, which is conducted on a periodic basis (e.g. every 5 minutes), it occurs that a determined aircraft is not where it ought to be, ρ will be defined as the time difference between the actual position and the predefined position in the RBT. That is, if $\|\gamma(t) - \bar{\gamma}(t)\|_2 \neq 0$ is observed, then $\rho \in \mathbb{R}$ will be defined satisfying:

$$\|\gamma(t) - \bar{\gamma}(t + \rho)\|_2 = 0 \qquad (23)$$

This work focuses on those deviations that may occur in time as a consequence of the effect of the wind. Two possible cases are under consideration when a ρ is detected:

- The FMS is correcting the time deviation, ρ, changing some flight profile parameters.
- The FMS guidance functionality has not yet been activated because ρ is less than the alert value set on it.

Therefore, ρ is defined as a time function $\rho(t)$ that describes the time diversion between the RBT and the actually flown trajectory as a function of time. As shown in Figure 11, it is assumed that $\rho(t)$ at the beginning will increase, depending on the wind, until the maximum diversion allowed by the FMS is reached, ρ_{MAX}. Then the FMS corrections will force $\rho(t)$ to reach the condition $\|\gamma(t) - \bar{\gamma}(t)\|_2 \approx 0$ again. When a time diversion, namely ρ_0 is observed, the most conservative period $[t_a, t_0]$ is selected for considering the duration of the time diversion.

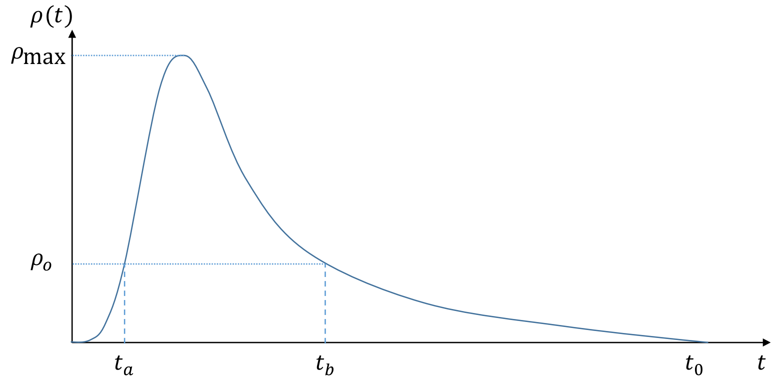


Figure 11: Evolution of $\boldsymbol{\rho(t)}$ while FMS corrects the time diversion

5.1 Estimation of the time uncertainty

In this section a model to study how a RBT time diversion is corrected by FMS intervention will be presented. This model will analyze how the FMS corrects the along-track diversions changing the flight profile. Furthermore, to properly present this model, some theoretical concepts and the work hypothesis are given.

5.1.1 Theoretical concepts of the 4D Navigation

A spatial waypoint is a three-dimensional point composed of longitude, latitude and altitude. In a 4-dimensional navigation a specific sequence of spatial waypoints that are registered at a required time instance, and are commonly referred to as time stamps, are defined. In this context a set of several variables and parameters which define the flight profile configuration, is specified in order to reach the 4D navigation points. The true airspeed is considered as the most important control variable in the flight profile configuration to achieve a waypoint at a given timestamp, according to (Mohleji, 1989).

True airspeed $\mathrm{V_{TAS}}$ is the speed of the aircraft relative to the air mass in which it is flying. The vector relationship between the $\overrightarrow{V_{TAS}}$ and the speed with respect to the ground, $\overrightarrow{\mathrm{V_G}}$, is: $\overrightarrow{\mathrm{V_{TAS}}} = \overrightarrow{\mathrm{V_G}} \pm \overrightarrow{\mathrm{V_W}}$, where $\overrightarrow{\mathrm{V_W}}$ is the wind speed vector. Aircraft flight instruments, however, do not compute true airspeed as a function of groundspeed and wind speed. They use impact and static pressures as well as a temperature input. The result is the true physical speed of the aircraft, relative to the surrounding body of air. To be more precise, at cruise level a flying aircraft uses as a speed indicator the Mach number, M, which relates the true airspeed with the speed of sound. The relation between this speed indicator and the true airspeed is $V_{TAS} = M \cdot a$, where a is the speed of sound, the speed at which the pressure waves travel through a fluid. More detailed and rigorous formulation can be found in the *BADA User Manual V 3.12* (Eurocontrol, 2014) and the *Revision of atmosphere model in BADA aircraft performance model 2010* (Eurocontrol, 2010).

A bearing refers to the direction or course that an aircraft has to take in order to reach a particular waypoint. The bearing of an aircraft over the great circle track is not constant, however, when the distance between two waypoints is small, the initial bearing value is close to the final bearing value. Hence, the initial bearing can be taken as a constant bearing value set on the aircraft FMS to reach a particular final waypoint, if it is close enough. The most used expression to compute the initial bearing is (Williams, 2012):

$$B_0 = atan2(\sin(lon_1 - lon_2)\cos(lat_2), \cos(lat_1)\sin(lat_2) - \sin(lat_1)\cos(lat_2)\cos(lon_1 - lon_2)))\ mod\ 2\pi$$

The last concept to be discussed is the time estimation and the wind effect. The time that an aircraft spends moving from an initial waypoint $x_1 = (lat_1, lon_1, alt)$ to a final waypoint $x_2 = (lat_2, lon_2, alt)$ can be represented as follows:

$$\mathrm{t} = \frac{1}{\beta}\left(\frac{\mathrm{d}}{|\overrightarrow{\mathrm{V_G(z)}}|}\right) \qquad (24)$$

where $|\overrightarrow{V_G(z)}|$ is the module of the ground airspeed vector of the aircraft at a given altitude z, d is the distance between the two waypoints and β is a conversion factor from *knots* to *feet/seconds.* However, since the ground speed is related to the true airspeed, the along-track wind has to be taken into account to express equation 24 in terms of the true airspeed. The effect of the along-track wind over the aircraft true airspeed in cruise level is associated with two elements (Mohleji, 1989):

- The direction of the wind with respect to the aircraft bearing. Depending of the relationship between the heading of the along-track wind and the aircraft, it is called tailwind or headwind.
- The magnitude of the along-track wind which represents the constant speed of the wind at a given altitude (cruise altitude).

The along-track component of wind in the horizontal plane can be represented as follows:

$$W(z) = V_W(z)\cos(|B - H_W(z) \pm \eta|) \qquad (25)$$

where $\mathrm{V_W(z)}$ is the speed of the wind at a given altitude, $\mathrm{H_W(z)}$ is the heading of the wind at a given altitude, η is the factor to correct the magnetic north to true north and the B is the Bearing of the aircraft's track. With this expression, equation 24 can be rewritten in terms of the true airspeed as follows:

$$\mathrm{t} = \frac{1}{\beta}\left(\frac{\mathrm{d}}{|\overrightarrow{\mathrm{V_{TAS}(z)}}| \pm \mathrm{W(z)}}\right) \qquad (26)$$

RBT timestamps are obtained using equation 26 with the $W_{for}(z)$ forecasted values. Predictive models are used to obtain wind velocity values during the flight to estimate the timestamps associated to each waypoint. Time diversion can appear during the flight if the wind real velocity values, W_{act}, are different to the predicted ones, making the FMS acts in order to ensure TBO navigation concept. Therefore, the following variable are defined in the model:

- V_{TAS} : The standard true airspeed for an aircraft at the cruise level.
- $V_{TAS\,max}$: The maximum true airspeed for an aircraft at a cruise level.
- V_{RBT} : The ground speed of an aircraft computed taking into account the forecasted values for the winds, W_{for}. Therefore, $V_{RBT} = V_{TAS} \pm W_{for}$.
- $V_{RBT\,max}$: The maximum ground speed of an aircraft computed taking into account the forecasted values for the winds.
- ΔW : The wind diversion between the forecasted winds and the actual ones, $\Delta W(z) = W_{for}(z) - W_{act}(Z)$.

5.1.2 Working hypothesis of the model

In this section the working hypothesis for the model is described. The model will show how a time diversion $\rho(t_0)$ detected by the FMS of an aircraft will be reduced to zero ($\rho(t_0) = 0$).

1. The initial time diversion that makes FMS acts is half a minute long, $\rho(\mathrm{t_0}) = 30\mathrm{sec}$.

2. Once a time diversion has been detected, the FMS will change the flight profile of the aircraft with the purpose of reducing diversion as fast as possible.
3. An aircraft flies during the cruise level to a constant Mach number.
4. To reestablish as soon as possible the initial 4D track, it is considered that the aircraft will flight over a straight line while the FMS corrects the time diversion.
5. The accelerations which are produced by a change in the flight profile conducted by the FMS, are to be considered as instant accelerations.

5.1.3 Time uncertainty model

The following model will present the particular case of the A320 aircraft, though it is perfectly extendable to any other aircraft changing technical specifications. However, this model should be seen as a simplified model developed to deal with time uncertainty, since it was developed under strict and simplified hypotheses. With it, it is intended to illustrate the robustness of the Constraint Programming model and that it is perfectly applicable in real situations where the data referring to the state of air traffic may contain certain levels of uncertainty.

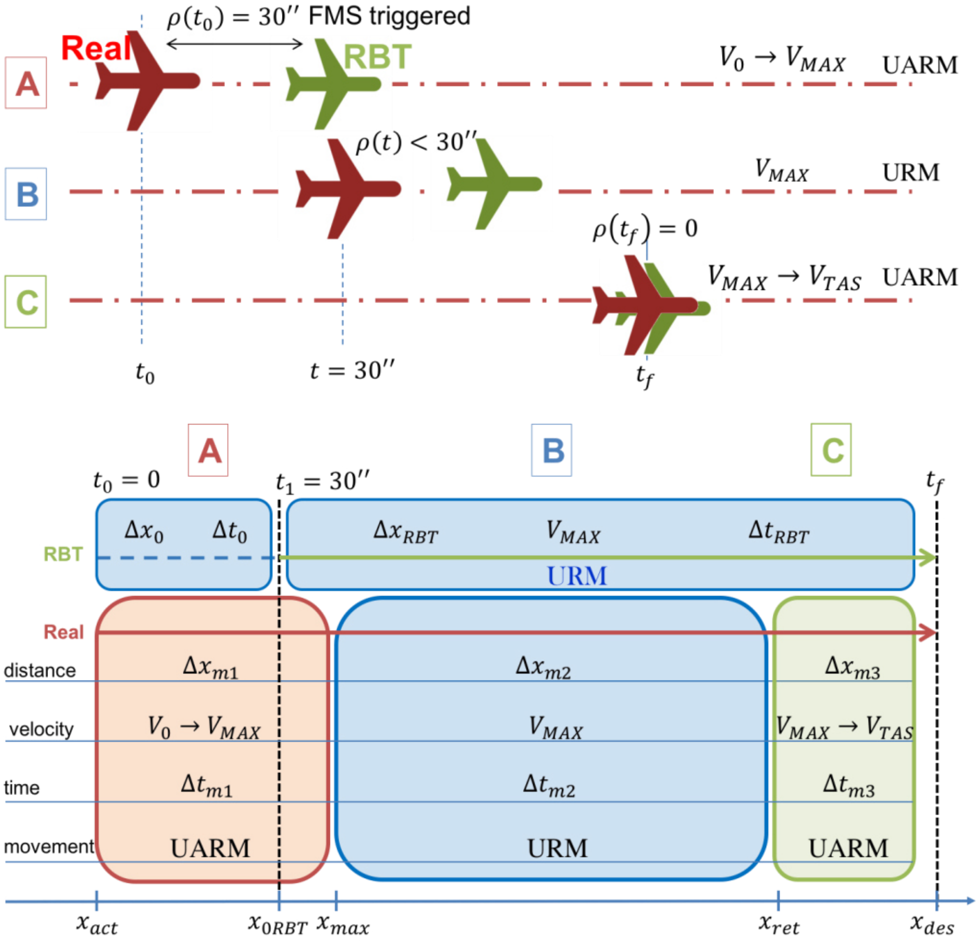
Let t_0 be the time instant in which the FMS of an A320 detects a time diversion ρ of a half minute, and let $x_{act} = (lat_{act}, lon_{act})$ be the point in which the aircraft is located at this t_0. The real flown trajectory is shifted one minute to respect the RBT trajectory, that is, an along-track diversion appears between the real flown and the RBT trajectories.

The distance Δx_0 separating the current position x_{act} of the aircraft with the position where it should be located, $x_{0RBT} = (lat_{0RBT}, lon_{0RBT})$, can be calculated taking into account that the RBT describes a trajectory flown at constant Mach Number (hypotheses 3). Distance Δx_0 is calculated following the atmospheric conditions, that is, taking into consideration temperature conditions and atmospheric pressure when computing V_{TAS}, and also taking into account the standard velocity in the cruise level for an A320 which is set to a constant Mach Number, $M = 0.78$ (Eurocontrol, 2014).

To correct a time diversion an aircraft must change its speed, and according to the working hypotheses, it will be considered that once the FMS detects this time diversion it will change the flight profile. The FMS will increase the engine power of the aircraft to reach the maximum velocity $V_{TAS\,max}$ to which an A320 can fly, M=0.84. Once this speed will be reached, the aircraft will continue flying at the same configuration until it overflows the point where the FMS will retrieve the initial flight profile. The whole system and the nomenclature used to describe this are illustrated in Figure 12.

Assuming, that the transitions between the engine configurations produce an instantaneous and constant acceleration (hypothesis 5), in physical terms the following movements must be performed by the aircraft (see Figure 12):

A. Uniformly accelerated rectilinear motion, UARM: between the starting point $x_{act} = (lat_{act}, lon_{act})$ where the A320 flies at speed $V_0 = V_{RBT} \pm \Delta W$ and the point $x_{max} = (lat_{max}, lon_{max})$ where the maximum velocity, $V_{MAX} = V_{RBT\,max} \pm \Delta W$, is reached.
B. Uniform rectilinear motion, URM: between point x_{max} and the point where the FMS will retrieve the initial flight profile $x_{ret} = (lat_{ret}, lon_{ret})$ at constant velocity V_{MAX}.
C. Uniformly accelerated rectilinear motion, UARM: between point x_{ret} and $x_{des} = (lat_{des}, lon_{des})$, where the actual trajectory coincides again with the RBT in space, time and velocity.



$$t_f = \Delta t_{m1} + \Delta t_{m2} + \Delta t_{m3} = 30'' + \Delta t_{RBT}$$

$$\Delta x_{RBT} + \Delta x_0 = \Delta x_{m1} + \Delta x_{m2} + \Delta x_{m3}$$

Figure 12: RBT vs. actual trajectory

Table 1: Equations of the three movements

Motion	Space	Time
UARM	$V_{MAX}^2 - V_0 = 2a_1 \Delta x_{m1}$	$\Delta t_{m1} = \frac{V_{MAX} - V_0}{a_1}$
URM	$\Delta x_{m2} = \Delta x_0 + \Delta x_{RBT} - \Delta x_{m1} - \Delta x_{m3}$	$\Delta t_{m2} = t_f - \Delta t_{m1} - \Delta t_{m3}$
UARM	$\Delta x_{m3} = \frac{V_{RBT}^2 - V_{MAX}^2}{2a_2}$	$\Delta t_{m3} = \frac{V_{RBT} - V_{MAX}}{a_2}$

The function $\rho(t)$, that is defined as the difference between the actual flown trajectory and the RBT for $t \in [t_b, t_0]$ (see Figure 11), can be calculated by solving the system of equations of the three movements described in Table 1. The values of parameters a_1 and a_2 are given and they depend on the aircraft type and the FMS system configuration. The authors in this work take the default values for a_1 and a_2 specified in the *BADA User Manual*. To extend the function $\rho(t)$ for the time interval $[t_a, t_b]$ it is assumed that the time diversion will increase until the FMS threshold will be reached. This increase will be calculated as a linear function taking into account the decrement in the ground speed of the aircraft due to the along-track wind effect.

5.1.4 Application of the model to treat time uncertainties

Supposing, that at some instance t_ρ a time diversion ρ is detected, then for every occupancy time window that overlaps the period $[t_a, t_0]$, the new entry time to the concurrence event cell must be recalculated using $\rho(t)$. Since at t_p it is unknown whether the function will decrease or increase because current FMS technology reacts only, when a certain deviation is present (in this case 1 minute), all possible cases must be covered by the solution space. Considering the starting position $\mathrm{t_p}$, there are two possible evolutions (see Figure 13) of the time diversion function $\rho(\mathrm{t})$:

1. The time diversion grows until the FMS guidance functionality is activated again
2. $\rho(t)$ recovers the delay

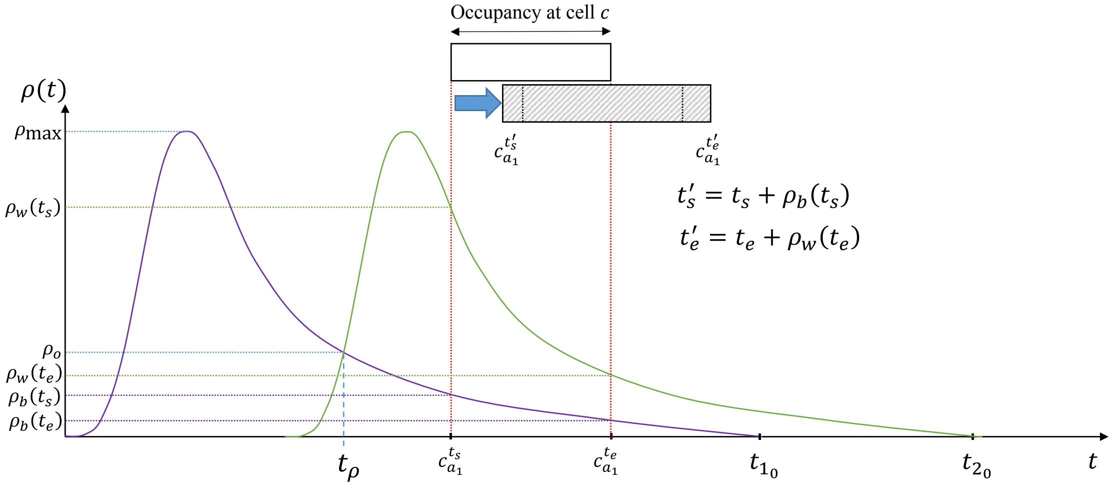


Figure 13: Effects of time diversion on conflict window.

Therefore, the times c_a^{ts} and c_a^{te} for each concurrence event in the period $[t_a, t_0]$ must be calculated for the two discussed cases and the best case for the start time $p_b(t_s)$ and the worst case for the end time $p_w(t_e)$ should be considered to ensure the required safety degree. It may happen that the new occupancy time of the cell will change, since the aircraft is changing its flight profile. Therefore, following condition is added to the CP model:

$$c_a^{ts} + p_b(t_s) \equiv soonest\ entry\ time \qquad (27)$$

$$c_a^{te} + p_w(t_e) \equiv latest\ exit\ time$$

6. APPLICATION AND EXPERIMENTAL RESULTS

The CP model was applied to four different realistic traffic scenarios obtained from Eurocontrol Demand Data Repository (DDR2) (Eurocontrol, 2017a). As stated by Eurocontrol, these data provide the most accurate picture of pan-European air traffic demand, from several years ahead until the day before operations. It can be used to support the Network Collaborative Planning Process that include strategic, seasonal and pre-tactical planning as well as for the planning of special events or major ATM evolution projects. Furthermore, the data offers improved 4D trajectories that are more accurate as all meaningful points are kept. Since the presented method highly relies on 4D trajectories this source of data was chosen. In this case, the input traffic data has been extracted by the Network Strategic Tool - NEST (EUROCONTROL) inside the Airspace Sector 1609, which is a dense traffic area at the en-route airspace sector above BeNeLux airspace.

To take the seasonality patterns in the aviation industry into account as stated in (ICAO, 2006), the scenarios were selected respectively. According to (European Commission, Eurocontrol and US Department of Transportation, 2016), the European traffic shows a clear peak during the summer months which, compared to average, has a 15% higher traffic volume. In this work, one traffic scenario was chosen in the winter period (January) and one traffic scenario was chosen in the summer period (July). Both days have two 1h traffic samples, one in the morning, and one in the afternoon to consider the daily traffic distribution. Table 2 shows the amount of concurrence events and RBTs of each scenario. The mapping of the traffic scenario for a given day takes less than 5 minutes in a standard desktop computer and the concurrence events detection of 2h of traffic takes less than 2 seconds.

Table 2: Information about the traffic scenarios

Scenario	**Date**	**Time**	**RBTs**	**Concurrence events**
Scenario 1	05.12.2017	08:00-09:00	44	59
Scenario 2	05.12.2017	15:00-16:00	55	79
Scenario 3	17.07.2017	08:00-09:00	44	49
Scenario 4	17.07.2017	15:00-16:00	121	216

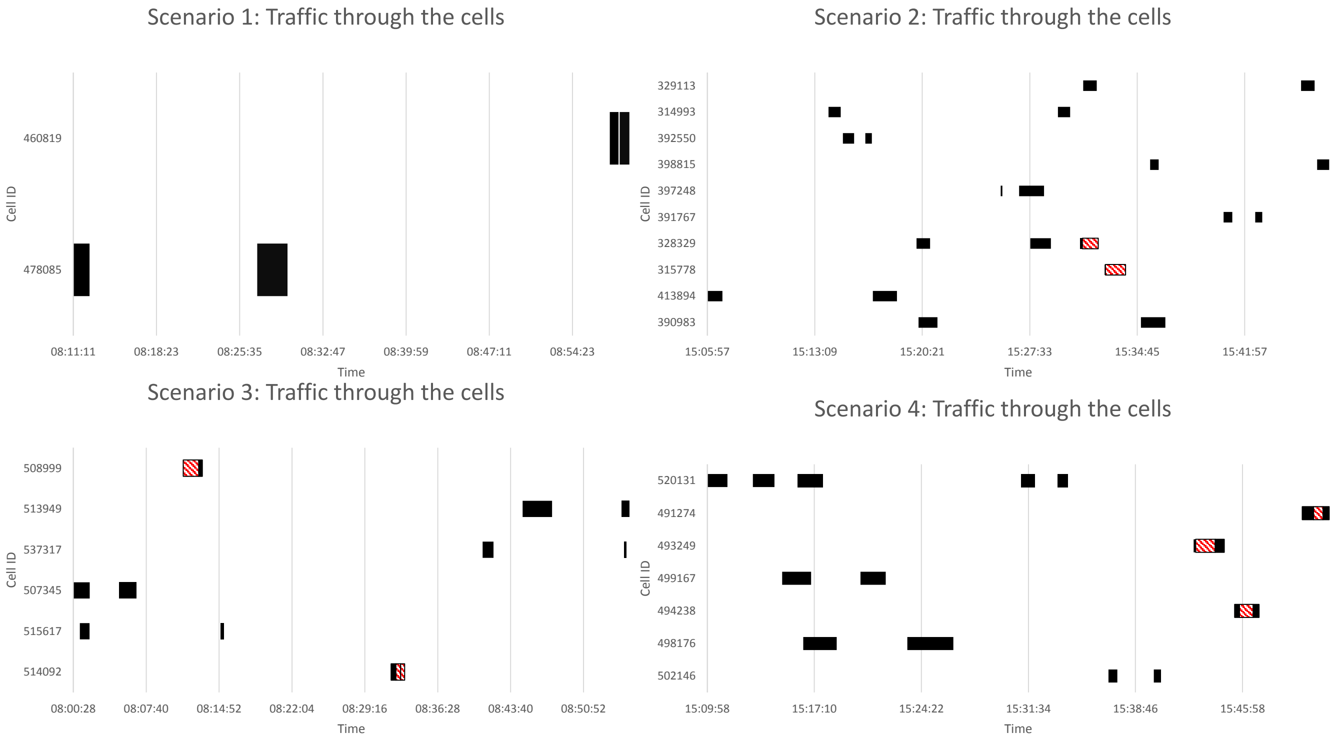
In the first set of experiments, we assumed TBO without uncertainties. In a second set of experiments, trajectories are manually modified creating a synthetic traffic scenario that considers uncertainties. A microanalysis is performed with a zoom into the cells to illustrate the effect of the uncertainty. In both experiments, the trajectories were discretized at each second, and each position was specified in terms of geographic coordinates and a time stamp. The cell size for the conflict detection was set to 6NM considering FL 190 to FL 460. The CP model has been implemented in Java and the following results were obtained. The solver was limited to 60 seconds to get the best suboptimal solution. All the experiments were performed on a Windows 7 computer with an Intel Core I5-4300M CPU 2.60GHz and 8GB RAM.

6.1 Experimental results without uncertainty

The detection and mitigation of the concurrence events are based on the algorithm presented in section 3 and 4. The scenarios presented in Table 2 are analysed in this work, leading from the detection of the concurrence events that have been used to find the optimal adjustment on the CTOT to mitigate the concurrence events and, therefore, possible ATC interventions.

In Figure 14, the traffic through the cells with potential concurrence events is shown. Since aircraft can be in conflict without sharing a cell (see neighborhood analysis in section 3), the virtual cell that sums up the concurrence events is represented in the figures. The cells with potential concurrence events are detected based on the RBT trajectories of those aircraft ready to depart but still on the ground according to their CTOT. En-route trajectories are considered to be conflict-free at the given time instant. As it can be seen in Figure 14, scenario 2, 3 and 4 have overlaps, indicated in red, whereas scenario 1 shows only potential concurrence events that could evoke an overlap. Figure 15 shows the traffic through the cells after applying trajectory adjustments. It can be seen that all potential concurrence events are removed by applying a combination of bounded slot time shifts on the CTOT and/or speed adjustments, leading to conflict free scenarios.

For all the scenarios, the CP model needs less than 0.04 seconds to find the best objective.


Scenario 1: Traffic through the cells

Scenario 2: Traffic through the cells

Scenario 3: Traffic through the cells

Scenario 4: Traffic through the cells

Figure 14: Gantt diagrams showing the traffic through the cells in FL 190 with potential concurrence events of those aircraft that can be shifted. The red striped cells indicate an overlap.

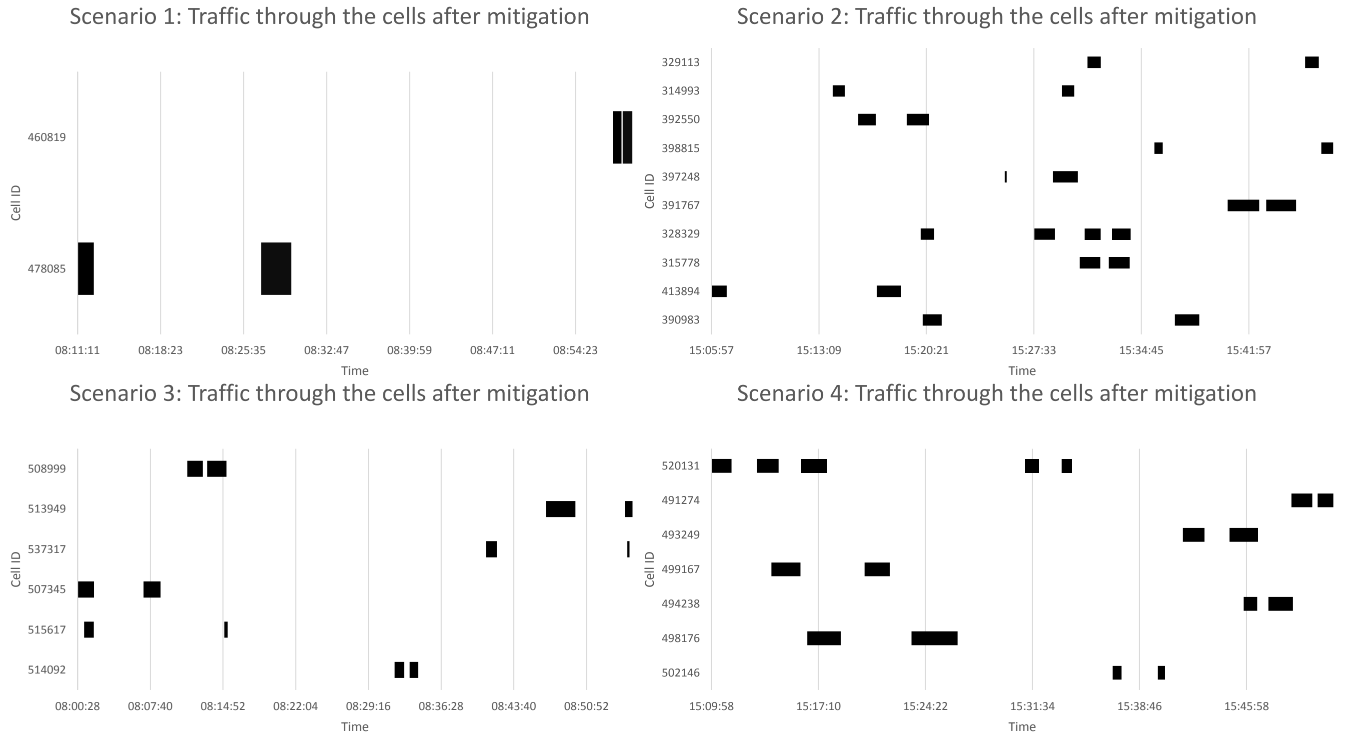
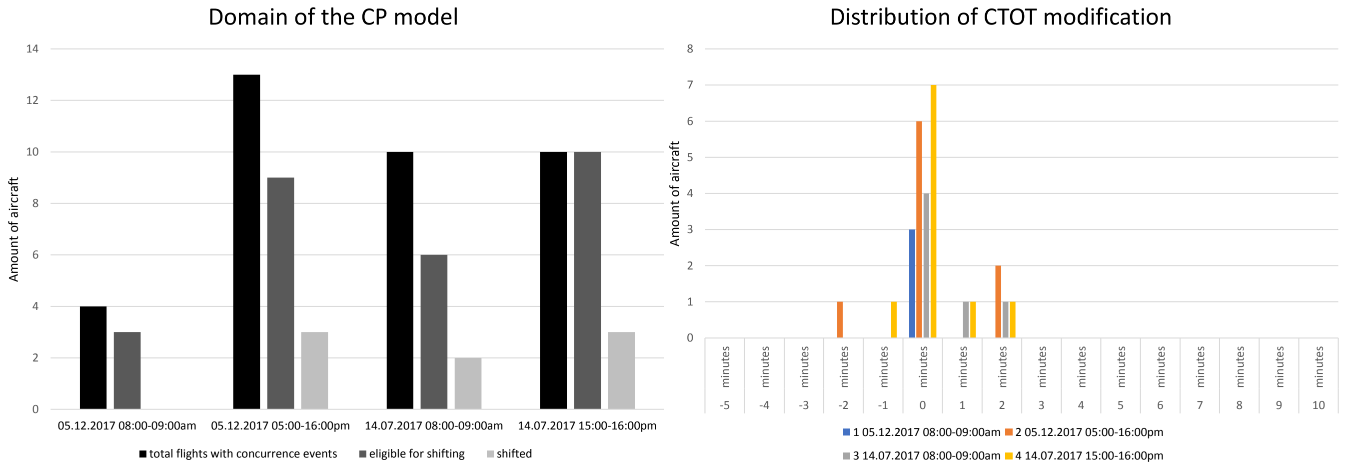


Figure 15: Traffic through the cells in FL 190 after applying the CP model solution. The diagram shows the conflict free solution after applying small adjustments on the CTOT and segment speed.

In Figure 16 (a), the number of aircraft that participate in a concurrence event, the number of aircraft whose CTOT can be modified, meaning they are still on the ground, and the number of actual shifted aircraft to solve the concurrence events for each scenario is shown. The distribution of the applied shifts on the CTOT gather around 0 minutes, see Figure 16 (b). This can be explained by the objective function that was defined in equation 22 that aims at minimizing the slot time shifts. The amount of concurrence events and RBTs which are around four times higher in scenario 4 than in the rest of the scenarios (see Table 2) do not influence the solution significantly.



(a) (b)

Figure 16: Diagrams showing the domain of the CP model and its solution. Diagram (a) shows how many aircraft are involved in a concurrence event, which of those aircraft are on the ground and can be modified and the solution which answers on how many of these aircraft have been modified to have conflict free traffic. (b) shows the distribution of the solution in shifted minutes on the CTOT.

6.2 Experimental results considering TBO time-uncertainty

Under the assumptions stated in section 5, the effects on the time diversion on the conflict window can be seen in Figure 17. For this experiment, a headwind of 50 knots or 92.6 km/h at FL 360 was assumed (ATSC113, 2017). The total time needed to recover the time diversion in this case is 10.6 minutes (636 seconds).

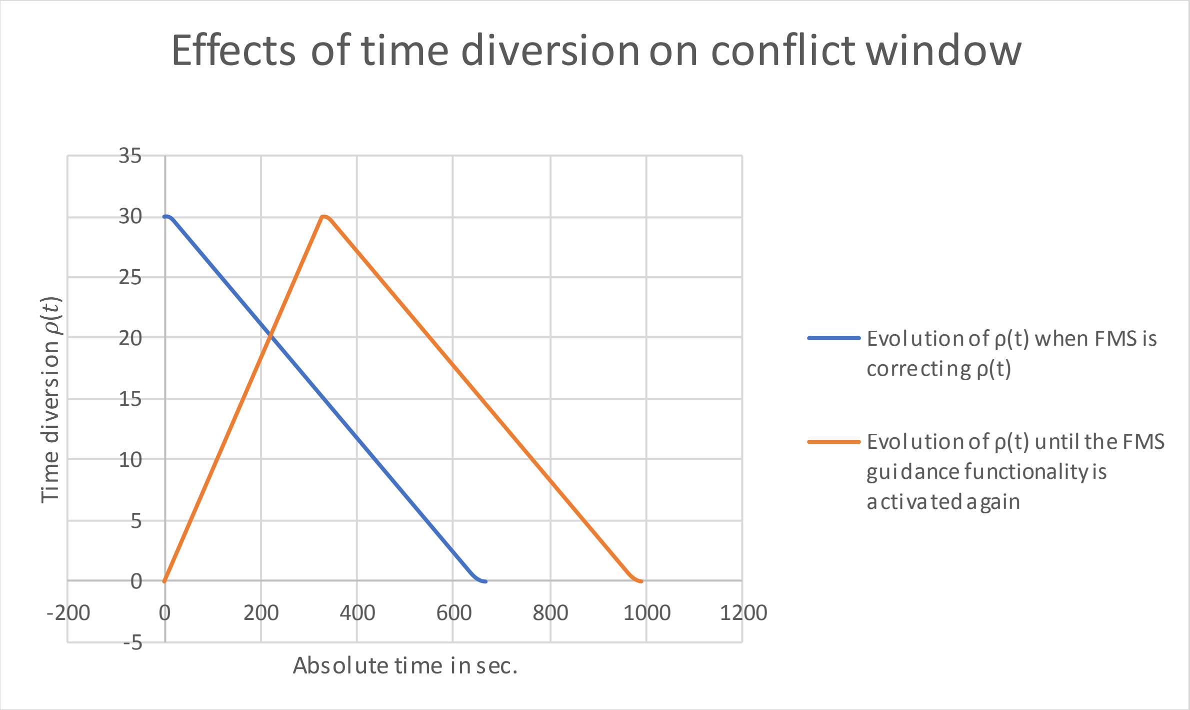


Figure 17: Effects of time diversion $\boldsymbol{\rho(t)}$ on conflict window of the experiment

To demonstrate the effect of the TBO time uncertainty on the concurrence event cells, the aircraft of scenario 1 have been modified. The modification was applied in such a way that half of the aircraft that are involved in a concurrence event and that belong to the solution space of the CP model, meaning that at least one of the aircraft in the concurrence event is still on the ground, are delayed. The size of the buffer which is added to the concurrence event cell is calculated as explained in equation 27. It was assumed, that the time diversion was detected 5 minutes before the first concurrence event of the aircraft.

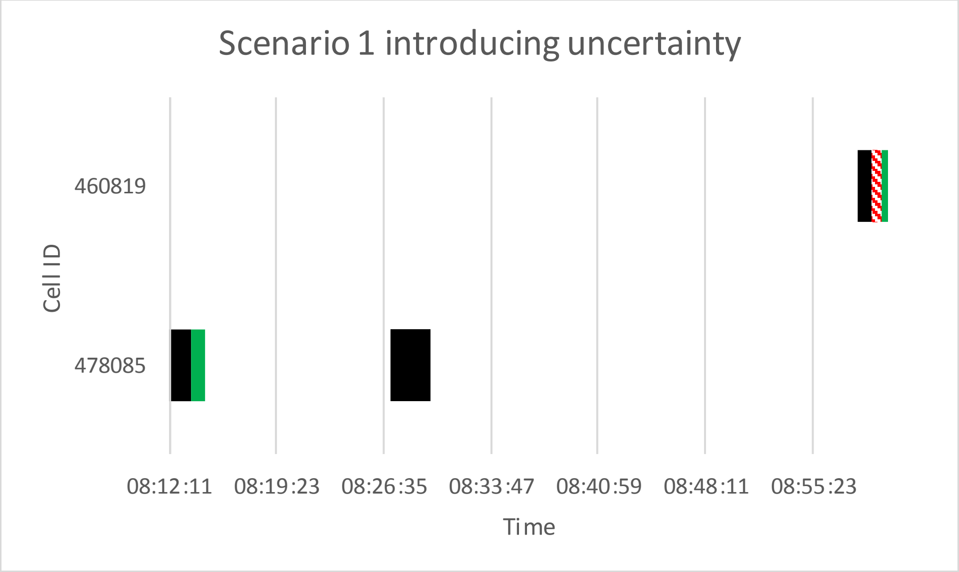


Figure 18: The diagram shows scenario 1 introducing a time diversion. Black time window represents the regular usage of the aircraft in the cell, green color indicates the safety buffer that was added to the time window and the red-striped color indicates an overlap. In cell 460819 a new overlap was evoked due to the shifting of one aircraft. In cell 478085 the safety buffer that is added to the cell which results as a consequence of the shifting of the aircraft can be seen in green colour.

The influence of the time diversion can be seen in Figure 18. In cell 478085 it can be seen that the first time window has increased in time. The green color indicates the safety buffer that was added to the time window which represents the usage of the aircraft in the cell according to equation 27. In cell 460819, the delay of the aircraft has evoked a new overlap. The CP model solves this concurrence event by applying a delay of -1 minute on the CTOT of one aircraft.

6.3 Other results

Despite the results of scenario 1-4 that are illustrated in this work, studies have been performed in previous work (Schefers et al. 2016) demonstrating the impact of the speed adjustments. In summary, an over-stressed realistic scenario composed of a set of 4,010 real 4D trajectories in the European airspace for a time window of 2 h, assuming TBO without uncertainties was analyzed. The bounded adjustments impose the actual take-off time to be within the [-5,10] minutes margin and the speed adjustments to be less than 10% of the RBT proposed by the airline. The observations that were made showed that in most of the cases the bounded speed adjustments are not enough to recover the effect of the applied slot time shifts. As it can be seen in Figure 19, the number of aircraft that do not meet their TTA is tightly related to the applied delay, as it can be observed from dotted curves. However, the average modification on flight duration is not related to the applied delay. The margins enabled by the bounded speed adjustments are not enough for compensating the applied delays. This fact could be overcome only if, first, solutions with lower absolute delays can be found (better search strategy) and, second, if the aircraft trajectory allows a bigger absolute elasticity. The latter condition does not depend on the solution method, but on the duration of the flight, on the number and relative positions of the proximate events involved and, mainly, on the airline constraints related to speed adjustments.

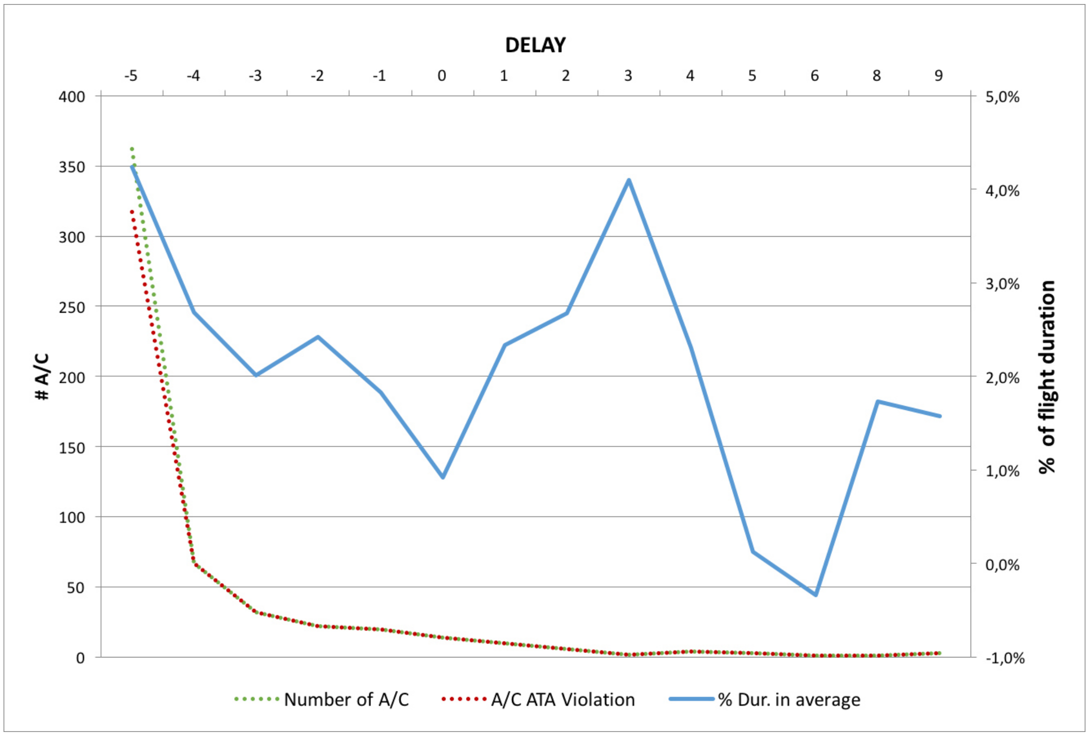


Figure 19: Blue line represents the average modification of flight duration with respect to the applied delay; dotted lines represent the number of A/C with the respective delay and the number of A/C not meeting their TTA (see online version for colours).

7. CONCLUSIONS AND FUTURE RESEARCH

In this work, an innovative, integrated approach combining conflict detection, and a mitigation mechanism considering trajectory prediction under uncertainty is presented. To tackle this system-level ATM problem, Reference Business Trajectories have been used as a source of data and powerful problem structuring tools have been designed that could manage and sustain air traffic growth. The research goal of this paper is to present a new CP mechanism to reduce the probability of separation minima infringement at the tactical level while preserving ATFM planned operations, taking into consideration time uncertainties and different flight levels. CP has been used to develop a constrained version of the ATM problem, allowing to separate the model formulation from the data and from the search strategy. The novelty of this efficient departure synchronization methodology that serves as a mitigation mechanism for concurrence events is that it considers the downstream effects of the applied measures while considering small departure adjustments, multi-flight levels, speed changes and time uncertainty.

The detection tool which provides the input for the CP concurrence events mitigation model has been proven to be a powerful tool that maps, detects and filters the traffic considering different FLs to retrieve a list with the tightest potential concurrence events for each pair of aircraft. The detection tool has been validated as part of the SESAR JU H2020 exploratory research projects PARTAKE and AGENT (SESAR JU, 2016, 2018) and is able to detect 2h of traffic in the entire European Civil Aviation Conference (ECAC) area in few seconds.

A method for dealing with along-track deviations is also proposed. The main goal of the presented model is to illustrate the effect of uncertainty on the concurrence event time window and to demonstrate how easily the mitigation model can take into account slight slot time shifts on the trajectory timestamps. The better estimate of the slot time shift the more robust the mitigation measures will be.

The CP model has been tested in a realistic scenario and it has been able to find an optimal solution in less than 40 milliseconds. Furthermore, the CP solver can find solutions that remove all conflicts, reducing the probability of separation minima infringement. The objective function allows to minimize the CTOT modifications to conduct conclusions that are as close to the original ATFM operations as possible. Feasible departure time configurations are determined by taking advantage of small freedom degrees provided by the flexible TBO synchronization mechanism that preserve the ATFM constraints.

The concept of time uncertainty which refers to stochastic variables that affects the temporal state of an aircraft or pre-departure information was integrated into the system to determine the impact of the deviation on the conflict window. With it, it is intended to illustrate the robustness of the Constraint Programming model and that it is perfectly applicable in real situations where the data referring to the state of air traffic may contain certain levels of uncertainty. The results of the effect of along-track deviations of the aircraft nominal routes were demonstrated by showing the development of the time diversion for one specific case and eliciting its impact on the conflict window.

Current forecasts and real-time locating systems and technologies are quite advanced. However, the here presented tools strongly rely on precise RBT information. Therefore, the methods explained in this article could be of greater importance from an operational point of view with the maturing of real-time information systems and the advancement of collaborative decision-making tools. Until the improvement of real-time information systems, future research could be carried out to understand the time window of look-ahead time in which the presented tools are the most effective.

During the experiments, it resulted that the amount of traffic is not an indicator for the number of concurrence events. It might be possible, that the complexity of the traffic and trajectory interdependencies effect the number of concurrence events. Future research should be dedicated towards analyzing trajectory interdependencies to support the CP solver to find optimal solutions, to determine the optimal airspace volume and the optimal environment for implementation (i.e. at airports with a lot of traffic movements) of the tools. It is also worth to mention the necessity to extend the mitigation model in order to include other operational constraints issued by Airports and Airspace Users. For instance, to ensure the proper use of the runway with additional information from the AMAN/DMAN, or the existence multiple runway feeders, etc. These kind of operational constraints can be easily added into the proposed CP model. This is one of the main advantages of the Constraint Programming paradigm. Finally, it would be of interest to study the development of the presented methodologies in a rolling horizon to see the reduction of the probability of separation minima infringement and ATC interventions.

Acronyms	***Meaning***
4D or 4DT	Trajectory described in terms of 3 spatial dimensions and time stamps 4-dimensional trajectories
AI	Artificial Intelligence
ATFM	Air Traffic Flow Management
ATFCM	Air Traffic Flow and Capacity Management
ATC	Air Traffic Control
ATM	Air Traffic Management
AU/AUs	Airspace user/ users
CD&R	Conflict Detection and Resolution
CP	Constraint Programming
CSP	Constraint Satisfaction Problem
CTOT	Calculated Take-Off Time
DA	Data Analytics
DDR2	EUROCONTROL Demand and Data Repository
DST	Decision Support Tools
ECAC	European Civil Aviation Conference
FL	Flight Level
FMS	Flight Management System
JJSP	Job Shop Scheduling Problem
NM	Nautical Miles
RBT	Reference Business Trajectory
SDS	Spatial Data Structure
SESAR	Single European Sky ATM Research
SOCSP	Single Objective Optimization Constrained Scheduling Problem
STAM	Short-Term ATFCM Measures
SWIM	System Wide Information Management
TBO	Trajectory Based Operations
TMA	Terminal Manoeuvring Area
TTA	Target Time of Arrival

ACKNOWLEDGEMENTS

This research is supported by the European Union's Horizon 2020 research and innovation program. The Project related to this research is PARTAKE "Cooperative departures for a competitive ATM network service" with Grant Agreement No. 699307.

REFERENCES

Adacher, L., Flamini, M. and Romano, E. (2017) 'Rerouting algorithms solving the air traffic congestion Advanced PID tuning based on the modulus optimum method for real systems Rerouting Algorithms Solving The Air Traffic Congestion', *International Conference on Applied Mathematics and Computer Science AIP Conference Proceedings AIP Conference Proceedings*, 10(10), pp. 20053–20060. doi: 10.1063/1.4981999.

Allignol, C., Barnier, N., Flener, P. and Pearson, J. (2012) 'Constraint programming for air traffic management : a survey Constraint programming for air traffic management : a survey Constraint programming for air traffic management: A survey In memory of Pascal Brisset', *Knowledge Engineering Review*. Cambridge University Press Cambridge University Press, 270(00), pp. 361–392. doi: 10.1017/S0000000000000000.

ATSC113 (2017) *UBC ATSC113 crosswinds and headwinds*. Available at: https://www.eoas.ubc.ca/courses/atsc113/flying/met_concepts/02-met_concepts/02d-crosswind/index.html (Accessed: 29 January 2018).

Barnier, N. and Allignol, C. (2009) '4D-trajectory deconfliction through departure time adjustment', in *8th USA/Europe Air Traffic Management Research and Development Seminar*.

Barnier, N. and Brisset, P. (2004) 'Graph Coloring for Air Traffic Flow Management', *Annals of Operations Research*. Kluwer Academic Publishers, 130(1–4), pp. 163–178. doi: 10.1023/B:ANOR.0000032574.01332.98.

Van Beek, P. (2006) 'Chapter 4 Backtracking search algorithms', in *Handbook of Constraint Programming*. Elsevier B.V., pp. 85–134. doi: 10.1016/S1574-6526(06)80008-8.

Bessiere (2006) 'Constraint Propagation', *Elsevier*, (Handb. Constraint Program.), p. chapter 3, pages 29–83.

Casado, Goodchild and Vilaplana (2012) 'Identification and Initial Characterization of Sources of Uncertainty Affecting the Performance of Future Trajectory Management Automation Systems', in *Proceedings of the 2nd International Conference on Application and Theory of Automation in Command and Control Systems*. IRIT Press Toulouse, France, pp. 170–175.

Castelli, L., Pesenti, R. and Ranieri, A. (2011) 'The design of a market mechanism to allocate Air Traffic Flow Management slots', *Transportation Research Part C: Emerging Technologies*, 19(5), pp. 931–943. doi: 10.1016/j.trc.2010.06.003.

Chaimatanan, S., Delahaye, D. and Mongeau, M. (2018) 'Hybrid metaheuristic for air traffic management with uncertainty', in Amodeo, L., Talbi, E., and Yalaoui, F. (eds) *Recent developments of metaheuristic*, pp. 219–25.

Chemla, D., Diaz, D., Kerlirzin, P. and Manchon, S. (1995) 'Using clp(FD) to Support Air Traffic Flow Management', in *3rd International Conference on the Practical Application of Prolog*. Paris, France.

Çinar, E. and Demirel, S. (2017) 'EUROCONTROL SLOT ALLOCATION METHODOLOGY AND NEW APPROACH FOR CALCULATED TAKE OFF TIMES (CTOT): ALTERNATIVE CTOT VERSUS CTOT', 18(1), pp. 69–77. doi: 10.18038/aubtda.300428.

Envisa (2017) *Environmental Costs and Benefits of Ground Delay - Envisa - Aviation & Environmental Solutions*. Available at: http://www.env-isa.com/en/expertise/environmental-costs-and-benefits-of-ground-delay-2/ (Accessed: 15 May 2017).

Eurocontrol (2010) *EUROCONTROL EXPERIMENTAL CENTRE REVISION OF ATMOSPHERE MODEL IN BADA AIRCRAFT PERFORMANCE MODEL*.

Eurocontrol (2014) 'USER MANUAL FOR THE BASE OF AIRCRAFT DATA (BADA) REVISION 3.12'.

Eurocontrol (2017a) *Demand Data Repository (DDR) | Eurocontrol*. Available at: http://www.eurocontrol.int/ddr (Accessed: 28 December 2017).

Eurocontrol (2017b) *Short-term ATFCM measures: building on the local flow management process | Eurocontrol*. Available at: https://www.eurocontrol.int/articles/short-term-atfcm-measures-building-local-flow-management-process (Accessed: 29 September 2017).

Eurocontrol (2017c) *Trajectory-Based Operations - EUROCONTROL ATM Lexicon*. Available at: https://ext.eurocontrol.int/lexicon/index.php/Trajectory-Based_Operations (Accessed: 2 December 2017).

European Commission, Eurocontrol and US Department of Transportation (2016) 'Comparison of Air Traffic Management-Related Operational Performance: U.S./Europe 2 0 15'. Available at: https://www.faa.gov/air_traffic/publications/media/us_eu_comparison_2015.pdf (Accessed: 29 December 2017).

Ferguson, J., Kara, A. Q., Hoffman, K. and Sherry, L. (2013) 'Estimating Domestic U.S. Airline Cost of Delay based on European Model', *Transportation Research Part C: Emerging Technologies*, 33, pp. 311–323.

Flener, P., Pearson, J., Garcia-Avello, C., Ç eliktin, M. and Dissing, S. (2007) 'Air-Traffic Complexity Resolution in Multi-Sector Planning Using Constraint

Programming Directorate of ATM Programmes, ATC Applications and Systems Division Directorate of ATM Strategies, SESAR and ATM Strategy Division Directorate of ATM Programmes, Comm', in FAA/EUROCONTROL (ed.) *Proceedings of the USA/FAA Air Traffic Management R&D Seminar 2007*. Barcelona, Spain, p. 378.

Van Hentenryck, P., Simonis, H. and Dincbas, M. (1992) 'Constraint satisfaction using constraint logic programming', *Artificial Intelligence*. Elsevier Science Publishers Ltd., 58(1–3), pp. 113–159. doi: 10.1016/0004-3702(92)90006-J.

IATA (2017) *IATA - IATA Forecasts Passenger Demand to Double Over 20 Years*. Available at: http://www.iata.org/pressroom/pr/Pages/2016-10-18-02.aspx (Accessed: 2 December 2017).

IBM (2015) *IBM ILOG CPLEX Optimization Studio OPL Language User's Manual*. Version 12. Edited by IBM.

ICAO (2006) 'International Civil Aviation Organization Manual on Air Traffic Forecasting'. Available at: https://www.icao.int/MID/Documents/2014/Aviation Data Analyses Seminar/8991_Forecasting_en.pdf (Accessed: 29 December 2017).

ICAO (2016) 'Doc 4444', in *Procedures for Air Navigation Services Air Traffic Management*. Montréal, Quebec, Canada, pp. 1–464.

Kerlirzin, P., Manchon, S., Plusquellec, C. and Gotteland, J. B. (2000) 'Building and evaluating a minimal regulation scheme', in *3rd USA/Europe Air Traffic Management Research and Development Seminar*. Napoles, Italy.

Kuenz (2015) *High Performance Conflict Detection and Resolution for Multi-Dimensional Objects*. Gottfried Wilhelm Leibniz Universität Hannover, Germany.

Van Leeuwen, P., Van, N. and Houwert, H. (2003) *Scheduling aircraft using constraint relaxation*.

Liang, M., Delahaye, D. and Maréchal, P. (2017) 'Integrated sequencing and merging aircraft to parallel runways with automated conflict resolution and advanced avionics capabilities', *Transportation Research Part C: Emerging Technologies*, 85, pp. 268–291. doi: 10.1016/j.trc.2017.09.012.

Marcella, S., Andrea, D., Paolo, D. and Pacciarelli, D. (2017) 'Scheduling models for optimal aircraft traffic control at busy airports: Tardiness, priorities, equity and violations considerations', *Omega*. Pergamon, 67, pp. 81–98. doi: 10.1016/J.OMEGA.2016.04.003.

Marriott, K. and Stuckey, P. J. (1998) *Programming with constraints : an introduction*. MIT Press.

Masalonis, A. J., Callaham, M. B. and Wanke, C. R. (2003) 'DYNAMIC DENSITY AND COMPLEXITY METRICS FOR REALTIME TRAFFIC FLOW MANAGEMENT', in *Budapest/ Hungary 5th USA/ Europe Air Traffic Management R&D Seminar*.

Mohleji, S. C. (1989) 'Optimal flight management system utilization with ATC automation', *IEEE Aerospace and Electronic Systems Magazine*, 4(2), pp. 26–32. doi: 10.1109/62.16993.

Mondoloni, S. (2006) 'Aircraft Trajectory Prediction Errors: Including a Summary of Error Sources and Data (Version 0.2) FAA/Eurocontrol Action Plan 16 Common Trajectory Prediction Capabilities'. Available at: https://acy.tc.faa.gov/data/_uploaded/Publications/tjm/TP_Sens_v02.pdf (Accessed: 11 December 2017).

Netjasov, F., Janić, M. and Tošić, V. (2011) 'Developing a generic metric of terminal airspace traffic complexity', *Transportmetrica*. Taylor & Francis Group, 7(5), pp. 369–394. doi: 10.1080/18128602.2010.505590.

Nosedal, J., Piera, M. A., Ruiz, S. and Nosedal, A. (2014) 'An efficient algorithm for smoothing airspace congestion by fine-tuning take-off times', *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, 44, pp. 171–184. doi: 10.1016/j.trc.2014.03.017.

Nosedal, J., Piera, M. A., Solis, A. O. and Ferrer, C. (2015) 'An optimization model to fit airspace demand considering a spatio-temporal analysis of airspace capacity', *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, 61, pp. 11–28. doi: 10.1016/j.trc.2015.10.011.

Pabst, T., Kunze, T., Schultz, M. and Fricke, H. (2013) 'Modeling external disturbances for aircraft in flight to build reliable 4D trajectories', in *3rd International Conference on Application and Theory of Automation in Command and Control Systems*. Napoli, Italy.

Piera, M. A., Ramos, J. J., Moreno, R. and Narciso, M. (2014) 'Causal simulation models for facing third millennium air transport sustainability', *SIMULATION*. SAGE PublicationsSage UK: London, England, 90(2), pp. 162–170. doi: 10.1177/0037549712469247.

Qian, X., Mao, J., Chen, C.-H., Chen, S. and Yang, C. (2017) 'Coordinated multi-aircraft 4D trajectories planning considering buffer safety distance and fuel consumption optimization via pure-strategy game', *Transportation Research Part C: Emerging Technologies*. Pergamon, 81, pp. 18–35. doi: 10.1016/J.TRC.2017.05.008.

Rossi, F., Van Beek, P. and Walsh, T. (2006) 'Handbook of Constraint Programming', *Elsevier*.

Rossi, F. and Saraswat, V. (2006) 'Constraint Programming Languages for Big Data Applications'.

Ruiz, S., Piera, M. A., Nosedal, J. and Ranieri, A. (2014) 'Strategic de-confliction in the presence of a large number of 4D trajectories using a causal modeling approach', *Transportation Research Part C: Emerging Technologies*. Pergamon, 39, pp. 129–147. doi: 10.1016/J.TRC.2013.12.002.

Ruiz, S., Piera, M. A. and Del Pozo, I. (2013) 'A Medium Term Conflict Detection and Resolution system for Terminal Maneuvering Area based on Spatial Data Structures and 4D Trajectories', *Transportation Research Part C: Emerging Technologies*. Pergamon, 26, pp. 396–417. doi: 10.1016/J.TRC.2012.10.005.

Schefers, N., Ramos, J. J. and Nosedal, J. (2016) 'An efficient constraint programming model for cooperative flight departures', *Proceedings of HMS 2016*, pp. 13–22. Available at: http://www.msc-les.org/proceedings/hms/hms2016/hms2016_13.html (Accessed: 10 August 2018).

Sesar (2015) 'THE ROADMAP FOR DELIVERING HIGH PERFORMING AVIATION FOR EUROPE European ATM Master Plan', Edition 20, p. 126.

SESAR JU (2016) *Agent*. Available at: http://www.agent-aero.eu/ (Accessed: 31 January 2018).

SESAR JU (2018) *Partake*. Available at: http://www.partake-aero.eu/ (Accessed: 18 January 2018).

SKYbrary (2017) *4D Trajectory Concept - SKYbrary Aviation Safety*. Available at: https://www.skybrary.aero/index.php/4D_Trajectory_Concept (Accessed: 19 November 2017).

Trandac, H., Baptiste, P. and Duong, V. (2005) 'Airspace sectorization with constraints', *RAIRO - Operations Research*. EDP Sciences, 39(2), pp. 105–122. doi: 10.1051/ro:2005005.

Tselios, D. C., Savvas, I. K. and Kechadi, M. T. (2013) 'Multiple project portfolio scheduling using recurrent neural networks', *International Journal of Simulation and Process Modelling*, 8(4), p. 227. doi: 10.1504/IJSPM.2013.059421.

Vilardaga, S. and Prats, X. (2015) 'Operating cost sensitivity to required time of arrival commands to ensure separation in optimal aircraft 4D trajectories', *Transportation Research Part C: Emerging Technologies*. Pergamon, 61, pp. 75–86. doi: 10.1016/J.TRC.2015.10.014.

Wang, Z., Liang, M. and Delahaye, D. (2017) 'Short-term 4D Trajectory Prediction Using Machine Learning Methods', *Sesar innovation days 2017*.

Wilco, R. (2017) *Trajectory based operations (TBO)*. Available at: http://www.roger-wilco.net/do-you-really-understand—-trajectory-based-operations-tbo/ (Accessed: 2 December 2017).

Williams, E. (2012) *Aviation Formulary V1.46*.

Xu, Y. and Prats, X. (2017) 'Including Linear Holding in Air Traffic Flow Management for Flexible Delay Handling', in *Europe Air Traffic Management Research and Development Seminar*.

Chapter 9

9. Conclusion and future research

Aligned with the research motivation and objectives initially stated, the main objective of this work is to enhance the airspace demand-capacity balance by trying to reduce the potential air traffic controller interventions en-route. Towards this goal, tight interdependencies between aircraft trajectories are identified at network level and removed by rescheduling take-off times in such a way that target times of arrival are preserved within a one-minute margin. This can be seen as a short term ATFCM measure that enables an increase in airspace capacity by reducing the probability to lose separation minima and transferring the workload of controllers from conflict resolution and manoeuvre communication to traffic monitoring.

The proposed methodology is based on three modules and has been implemented and tested using realistic scenarios. Depending on the traffic scenario, 16-52% of the concurrence events are solved without having to make huge investments but simply by using the provided information and technologies to coordinate the departures.

The novelty of this efficient departure synchronization methodology that serves as a mitigation mechanism for concurrence events is that it considers the downstream effects of the applied measures while considering small departure adjustments, multi-flight levels, speed changes and time uncertainty.

Regarding the proposed research objectives of this doctoral thesis it can be concluded that all objectives have been reached. The Constraint Programming model that has been implemented generates the operational constraints for cooperative aircraft departures and the consideration of time uncertainty. Furthermore, the progress between paper 2 and paper 4 show the improvement of the detection tool and its' associated neighbourhood analysis. An analysis of trajectory time dependency dynamics was developed using graph theory to identify coupling and concurrence interdependencies. In a last step, the model was applied and tested using different realistic traffic scenarios. The outcomes are documented in the selected research papers.

Finally, by empowering TBO as a flexible synchronization mechanism, several challenges arise and new research opportunities emerge. During the experiments, it resulted that the amount of traffic is not an indicator for the number of concurrence events. It might be possible, that the complexity of the traffic and trajectory interdependencies effect the number of concurrence events. Future research should be dedicated towards analysing trajectory interdependencies to support the CP solver to find optimal solutions, to determine the optimal airspace volume and the optimal environment for implementation (i.e. at airports with a lot of traffic movements) of the tools.

Moreover, further research is required to apply different search strategies on different traffic scenarios favouring the selection of adjustments close to zero in first term. This way speed adjustment efforts are expected to be smaller. Also, further research is suggested to understand the cause of saturations and to develop best strategies on how to solve them.

Finally, it should be analysed towards which extend the application of the tools to a wider airspace including more operating airports could expand this possibility to mitigate further concurrence events. Also, the look ahead time for the tools should be analysed to obtain the most optimal solutions and a reasonable time-uncertainty impact.

10. Bibliography

Apt, K. & Wallace, M., 2006. Constraint logic programming using ECLiPSe. Available at: https://books.google.com/books?hl=de&lr=&id=yyrf6H86_ukC&oi=fnd&pg=PR9&dq=K.+Apt+and+M.+Wallace.+“Constraint+Logic+Programming+Using+ECLiPSe”.+Cambridge+University+Press,+2007&ots=HSV_Dyy5T5&sig=SpbtPPc54EIVrra1CR5dEIfj8U0 [Accessed September 9, 2018].

ATSC113, 2017. UBC ATSC113 crosswinds and headwinds. Available at: https://www.eoas.ubc.ca/courses/atsc113/flying/met_concepts/02-met_concepts/02d-crosswind/index.html [Accessed January 29, 2018].

Cook, A., 2007. *European air traffic management : principles, practice and research*, Available at: https://books.google.es/books/about/European_Air_Traffic_Management.html?id=vQ9LG6TWl9oC&redir_esc=y [Accessed May 11, 2017].

Eurocontrol, 2007. *HOURLY ENTRY COUNT VERSUS OCCUPANCY COUNT RELATIONSHIP DEFINITIONS AND INDICATORS (I)*, Available at: https://www.eurocontrol.int/sites/default/files/library/015_Hourly_entry_vs_occupancy_count_definitions_and_indicators.pdf.

Eurocontrol, 2018. Minimum Departure Interval - EUROCONTROL ATM Lexicon. Available at: https://ext.eurocontrol.int/lexicon/index.php/Minimum_Departure_Interval [Accessed May 28, 2018].

Van Hentenryck, P. & Michel, L., 2005. *Constraint-based local search*, MIT Press.

IBM, 2015. *IBM ILOG CPLEX Optimization Studio OPL Language User’s Manual* Version 12. IBM, ed.,

ICAO, 2016. Doc 4444. In *Procedures for Air Navigation Services Air Traffic Management*. Montréal, Quebec, Canada, pp. 1–464.

ICAO, 2005. International Civil Aviation Organization Global Air Traffic Management Operational Concept. Available at: https://www.icao.int/Meetings/anconf12/Document Archive/9854_cons_en[1].pdf [Accessed October 11, 2017].

ICAO, 2015. TBO CONCEPT BY THE ICAO ATMRPP. Available at: http://www.sesarju.eu/sites/default/files/documents/reports/Appendix_A_to_WP652_TBOCD_3.0.pdf [Accessed October 12, 2017].

Jefferson, C. et al., Implementing Logical Connectives in Constraint Programming. Available at: https://pn.host.cs.st-andrews.ac.uk/aij-watchedor-reify-paper.pdf [Accessed April 8, 2017].

N. Tamura, 2018. Cream: Class Library for Constraint Programming in Java. Available at: http://bach.istc.kobe-u.ac.jp/cream/ [Accessed September 9, 2018].

Netjasov, F., Janić, M. & Tošić, V., 2011. Developing a generic metric of terminal airspace traffic complexity. *Transportmetrica*, 7(5), pp.369–394. Available at: http://www.tandfonline.com/doi/abs/10.1080/18128602.2010.505590 [Accessed May 28, 2018].

Rossi, F., Van Beek, P. & Walsh, T., 2006. Handbook of Constraint Programming. *Elsevier.*

Schefers, N., González, J.J.R. & Nosedal, J., 2016. An efficient constraint programming model for cooperative flight departures. In *18th International Conference on Harbor, Maritime and Multimodal Logistics Modelling and Simulation, HMS 2016.*

Sesar, 2015. THE ROADMAP FOR DELIVERING HIGH PERFORMING AVIATION FOR EUROPE European ATM Master Plan. , Edition 20, p.126.

SESAR, 2017. SESAR Joint Undertaking | High performing aviation for Europe. Available at: https://www.sesarju.eu/ [Accessed May 28, 2018].

SESAR JU, 2012. SESAR Concept of Operations Step 1. Available at: http://www.sesarju.eu/sites/default/files/documents/highlight/SESAR_ConOps_Document_Step_1.pdf [Accessed October 12, 2017].

SKYbrary, 2017. 4D Trajectory Concept - SKYbrary Aviation Safety. Available at: https://www.skybrary.aero/index.php/4D_Trajectory_Concept [Accessed November 19, 2017].

Tselios, D.C., Savvas, I.K. & Kechadi, M.T., 2013. Multiple project portfolio scheduling using recurrent neural networks. *International Journal of Simulation and Process Modelling*, 8(4), p.227.

A. Appendix

Paper 5

The main focus of this paper lays in the analysis of the possible benefits of such a STAM procedure by applying the methodology to a high traffic density control sector located in the London Terminal Manoeuvring Area. Following this approach, it will be possible to give recommendations about the most efficient parameters for the algorithm: cell-size, look-ahead time and number of airports in operation. This novel concept tested on a realistic scenario allows to reduce the number of potential ATC interventions in an efficient manner.

STAM-based methodology to prevent concurrence events in a Multi-Airport System (MAS)

Nina Schefers(1), Manuel Angel Amaro Carmona(2)
Juan José Ramos González (3), Francisco Saez Nieto (4), Pau Folch (5)

(1)(3) Technical Innovation Cluster on Aeronautical Management, Universitat Autónoma de Barcelona, Sabadell (Barcelona), Spain.
(e-mail: ninarebecca.schefers@uab.cat), (e-mail: JuanJose.Ramos@uab.cat)
(2)(4) School of Aerospace Transport and Manufacturing (SATM), Cranfield University, Cranfield (Bedfordshire), United Kingdom.
(e-mail: m.a.amarocarmona@cranfield.ac.uk), (e-email: p.saeznieto@cranfield.ac.uk)
(5) Department of Research and Innovation, Aslogic, Rubí, Spain
(e-mail: pfolch@aslogic.es)

Abstract— Pre-tactically managing the imbalances of the network and organize the resources of the airspace is one of the main objectives of Dynamic Demand & Capacity balancing. Introducing Short-term Air Traffic Flow and Capacity Management measures such as minor ground delays or slight speed adjustments applied to a selected number of flights on the day of operations, supports the Dynamic Demand & Capacity balancing by reducing the traffic complexity and the probability of Air Traffic Controllers interventions. The collaborative decision-making process underlies this concept by discussing the optimal decision for processes. This paper introduces a consecutive methodology for detecting concurrence events, analysing their trajectory interdependencies and applying a mitigation measure to apply a strategic shifting of Estimated Take-Off Time (ETOT) within their Calculated Take-Off Time (CTOT) windows. The main focus of this paper lays in the analysis of the possible benefits of such a STAM procedure by applying the methodology to a high traffic density control sector located in the London Terminal Manoeuvring Area. Following this approach, it will be possible to give recommendations about the most efficient parameters for the algorithm: cell-size, look-ahead time and number of airports in operation. This novel concept tested on a realistic scenario allows to reduce the number of potential ATC interventions in an efficient manner.

Keywords— ***Short-Term ATFCM Measures (STAM), Dynamic Demand & Capacity Balancing (dDCB), Trajectory Interdependencies, Trajectory Based Operations (TBO), Air Traffic Management, Decision Support Tool, Graph Theory, Concurrence event detection and resolution, London Terminal Manoevring Area.***

1. INTRODUCTION

The growth of passenger traffic observed in the last 20 years (UK Department for Transport 2013) generated a forthcoming necessity to increase the airspace and airport capacity. The eventual distribution of the population around large cities and the capacity constraints on existing major airports led to build new airports and introduce the concept of Multi-Airport Systems (MAS) as a key mechanism to meet the future demand.

The European and US Air Traffic Management (ATM) systems are expected to be modernized based on the research and development activities coordinated by the Single European Sky ATM Research (SESAR) and the Next Generation Air Transportation System (NextGen) programmes (Sesar JU 2017; Next Gen Program 2017), respectively. The Trajectory-Based Operations (TBO) concept, in which the airspace user's (AU's) intentions are shared to all the interested parties, is the base of many proposed solutions. Regarding the Air Traffic Flow and Capacity Management (ATFCM) process, SESAR defined the Short-Term ATFCM Measures (STAM) as a mechanism that helps to improve the Demand and Capacity Balancing (DCB) activities by applying a set of pre-tactical measures few minutes before the departure time (Sesar JU 2017; Nosedal et al. 2014). STAM measures could target to the flight plan (e.g. re-routing, speed changes, delay departure or slot swapping) or to the airspace (e.g. use of some military areas, level-capping, sector re-configuration).

This paper presents a STAM-based methodology to reduce the probability of the number of Air Traffic Controller (ATC) interventions "*on air*" and the of loss of separation minima infringement in surrounding areas of the airports. The method proposes the application of minor changes in the Estimated Take-Off Time (ETOT) (within the -5/+10 minutes window defined by the Calculated Take-Off Time (CTOT)). Although, the concept could be used for *en-route* scenarios, in this study, it has been adopted to MAS. The terminal control areas are stablished in the vicinities of the airports and conform the junction between the control zones and the airways. The control area of a multi-airport system is characterized by recurrent traffic that is distributed among the different airports of the zone. Short-term air traffic demand is stablished based on expected traffic crossing each ATC sector. Applying minor changes to the take-off time of selected flights is useful in a MAS for several reasons. Firstly, the mixed outbound traffic from different airports comprises the main sources of interdependencies that increase the traffic complexity and the ATC workload. Secondly, the traffic is more predictable for terminal airspace operations, which reduces the uncertainty levels and improve the flexibility of the measures.

The presented methodology is composed by three main functionalities: detection, analysis, mitigation that are sensible to different parameters. Consequently, the research goal is to apply the STAM solution in a Terminal Manoeuvring Area (TMA) and understand the operating parameters of the methodology that are suitable to be applied for a specific MAS. To this end, a set of tools have been developed using the method and a set of simulation exercises have been designed to analyse and study suitable working conditions for the proposed methodology.

The improvement of the pre-departure sequence must be seamlessly introduced at airport level without disturbing controllers' strategy using collaborative procedures. This paper analyses the possible benefits of such a STAM procedure by applying the methodology to a high traffic density control sector (EGTTCAP) located into the London Terminal Manoeuvring Area (LTMA).

The paper is organized as follow: After a brief literature review in Chapter 1.1, a description of the mapping, detection, analysis and mitigation methodology is given in section 2. The operational context and case of study are detailed in section 3 and the obtained experimental results are discussed. Finally, section 4 provides the conclusions and future research possibilities.

1.1 State of the Art

Historically, the ATFCM activities have been based on metrics estimated at strategic level such as the *entry-count*, and more recently, the *occupancy* (Eurocontrol 2007). The number of aircraft that can be handled by the ATCs is limited by their workload. When the maximum capacity is about to be reached, the air traffic demand is limited by applying regulations to all the aircraft of the sector. Regulations produce delays or re-routings and have a direct impact on the environment and in the airlines strategy. From the ATM point of view, these measures are effective, because limiting the demand releases the system, but not efficient enough because it affects all the agents of the system. The results of limiting the demand is an eventual over-release of the airspace that reflects that the measures taken to avoid a likely high-demand situation were not based on a good prediction of the system. The current metrics do not provide enough detail to determine the effects of the expected demand in the ATCs workload. At this point, the DCB process requires more realistic ways to determine how an increase of the demand in a sector affects the number of ATC interventions, i.e. using machine learning and big data technologies to improve the forecasts or introducing the use of complexity metrics in the regulation process.

Complexity metrics have been studied since many years by different authors (Netjasov et al. 2011). Additionally, Air Navigation Service Providers (ANSP) could calculate their own complexity metrics to reconfigure the airspace according to the required capacity or to support the decision-makers to impose local restrictions, such as Minimum Departure Intervals (MDI) (Eurocontrol 2018b). The effects of these measures tend to be efficient in areas where many airports feed a high number of aircraft to a common sector (e.g. London TMA). Although the MDI could be considered a more dynamic process, the principle is based in limiting the demand of selected Standard Instrumental Departures (SID). Consequently, equally-distributed ground delays (e.g. "one each ten minutes") are applied to all the flights that use the affected SIDs. To determine the required interval, the measure *groups* the affected flights by SID and its purpose is limiting the entry-count/occupancy to the target sector like performed at strategic level during the DCB process. The process does not identify what are the actual effects of selected flights in the target sector nor in the ATC workload.

The methodology presented is supported by the calculation of more dynamic metrics based on short-term trajectory predictions that identifies the effects of each AU as a stand-alone element of the system. This process determines the effects of individual AUs in the number of ATC interventions by detecting the imminent and potential concurrence events of each flight that crosses the target volume. Then, it is proposed a small changes of the Estimated Take-Off Time (ETOT) of selected flights in order to reduce the probability of ATC interventions.

2. METHODOLOGY DESCRIPTION

This section defines the methodology used to implement the consecutive set of tools. From a modular decomposition point of view, the main functional areas are detection, analysis and mitigation.

The detection functionality identifies the concurrence events and it is split into two sub-modules: the mapping process and the filtering process. The analysis functionality refers to the identification of topologies of interdependencies that cannot be removed by ground delays constrained by the CTOT time-window. This analysis will be helpful for identifying the trajectories that should be removed from the problem formulation in the mitigation functionality to provide a robust departure coordination. The mitigation functionality calculates feasible time stamp domains considering multi-objective criteria to resolve the trajectory clusters. The modular structure proposed for the development of the tools and their associated algorithms is shown in Figure 1.

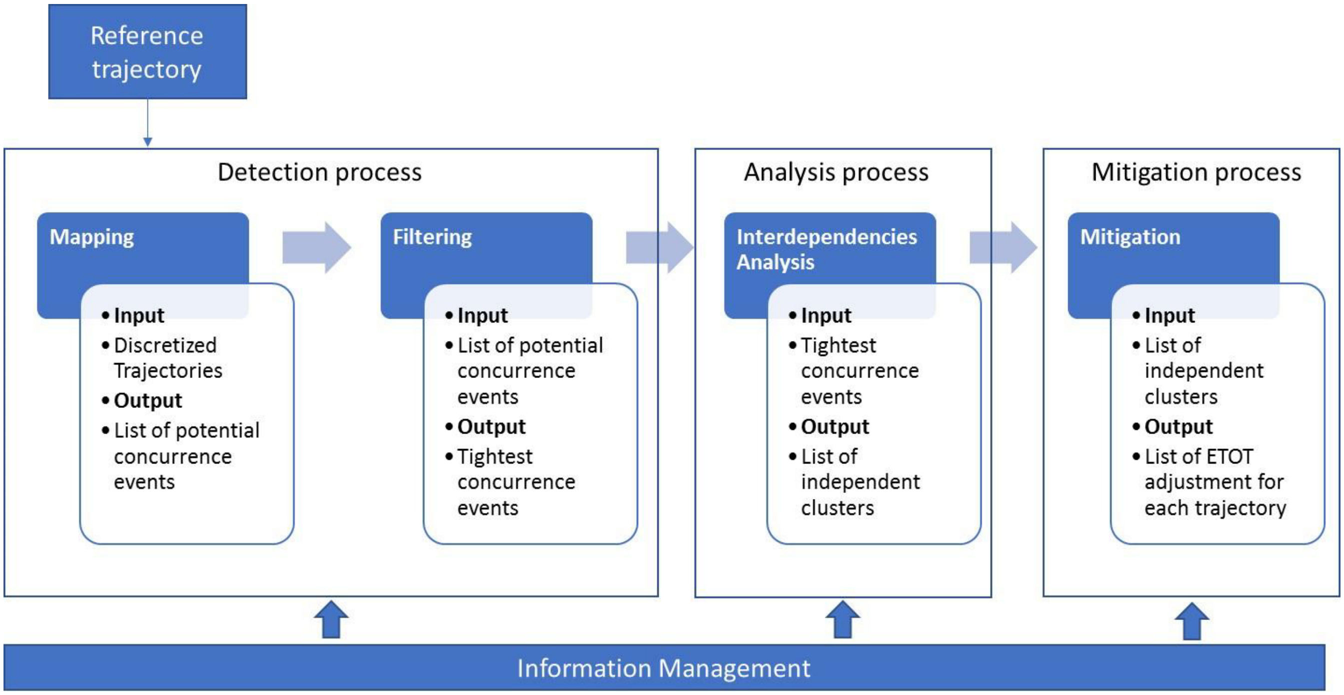


Figure 1: Modular structure of the tool

2.1 Detection Methodology

The mapping process includes on one hand the mapping of the trajectories onto a grid of cells covering the determined airspace and the spatio-temporal (S-T) interdependencies to identify potential concurrence events between trajectories that lose their safety buffer. The benefits of this methodology are the efficient way of identifying CE by partitioning the airspace and therefore being capable to promptly identify CE.

2.1.1 Mapping Process

To detect concurrence events, the airspace is partitioned into square cells with a size related to the lateral separation minima. The cell size is a parameter that depends on the operational environment (e.g. Terminal Manoeuvring Area or en-route). In this work, different operational parameters are tested to understand the behaviour of the tools and the correlation to the detected CE. 4D trajectories provide the benefit that the aircraft can fly on a practically unrestricted trajectory for as long as possible in exchange of being obliged to meet accurately any arrival time over a designated point (SKYbrary 2017).. To ensure the reliability of the concurrence event identification, the traffic in the surrounding cells is analysed using an intelligent neighbourhood check algorithm. After the initial mapping, cells that have an occupancy rate equal or greater than two aircraft simultaneously and/or neighbouring cells where two or more aircraft lose separation minima are identified, and stored in a matrix.

The second step of the mapping process is to process the entry and exit times of each aircraft trajectory into the cells, see Figure 2. With this information, the calculation of the temporal looseness (“clearance time” or “overlap time”) between pairs of aircrafts using the same cell can be determined. “Clearance time” refers to any time in which two aircraft do not share a cell. Logically, the smallest “clearance time” would be that one aircraft is just about to leave the cell and another aircraft is about to enter the cell. The temporal looseness H of two aircraft can be calculated by determining the minimum value of the exit time of the two aircraft and subtract the maximum entry time from this value h_m.

$$H \geq h_m \tag{1}$$

Where $h_m = [\delta_M - \delta_m] * 60$ measured in seconds and where $H \leq 0$ represents the temporal looseness of a clearance and $H > 0$ represents an overlap.

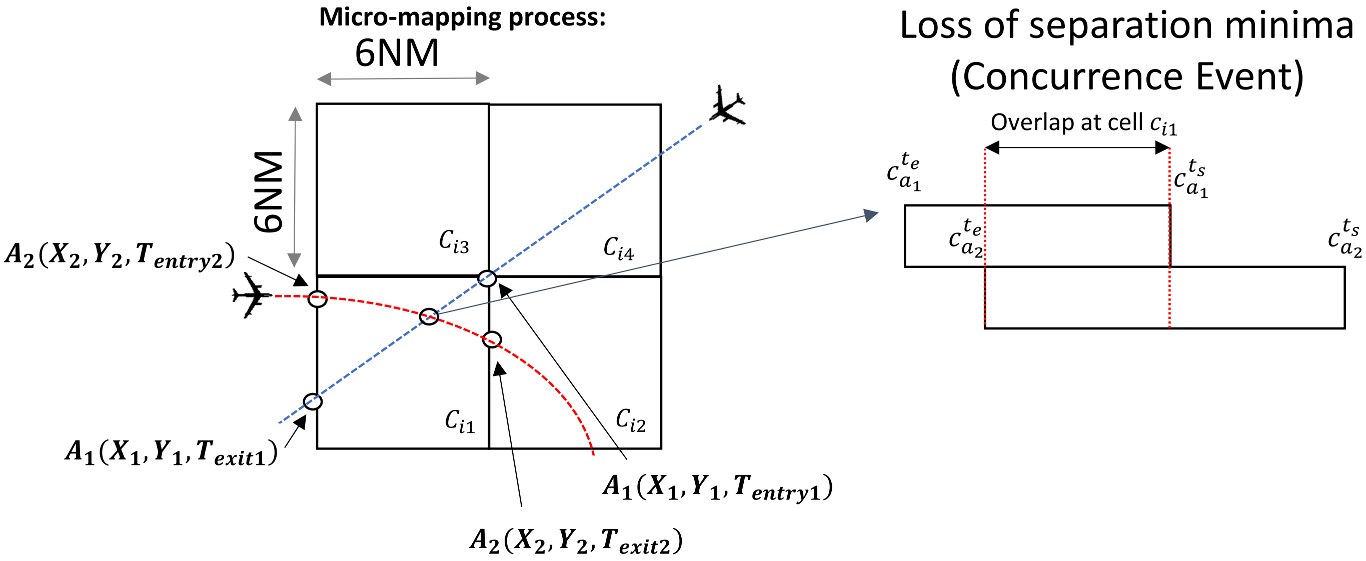


Figure 2: S-T Interdependency detection

2.1.2 *Filtering process*

Since not all the potential concurrence events are of interest for the mitigation process, the detected concurrence events are filtered by their temporal looseness. The domain for rescheduling the ETOT is restricted to the CTOT window of [-5, 10] minutes. Hence the greatest filtering value for temporal looseness is 15 minutes (900 seconds). Therefore, the list of the tightest potential concurrence events can be cut by all values exceeding this time frame because their spatial separation exceeds a maximum ETOT shifting window.

The idea behind this process is to focus on the tightest pair of aircraft that could lose separation minima when a shifting is applied to a flight. This process makes it feasible to develop a pre-tactical conflict detection methodology, capable of outperforming algorithms such as pairwise oriented detection or even Spatial Data Structure (SDS) methods (Lara 2005), with a performance sensible to scalability problems.

2.2 *Analysis Methodology*

The second module of the methodology is the Analysis tool. After the mapping and filtering process, several sets of pairwise potential concurrence events could be obtained. Using graph theory, the potential concurrence events detected in one cell at the same FL will form a node or vertex of a graph G and its edges will represent the interdependencies between potential conflicts.

2.2.1 *Analysis of Concurrence and Coupling Interdependencies*

After detecting the concurrence events, a set of trajectory interdependencies over the terminal airspace is represented. The output represents all concurrence events as being interrelated. The objective is to decompose the complex problem that is a conjunction of a huge amount of S-T interdependencies to reduce the complexity, see Figure 3.

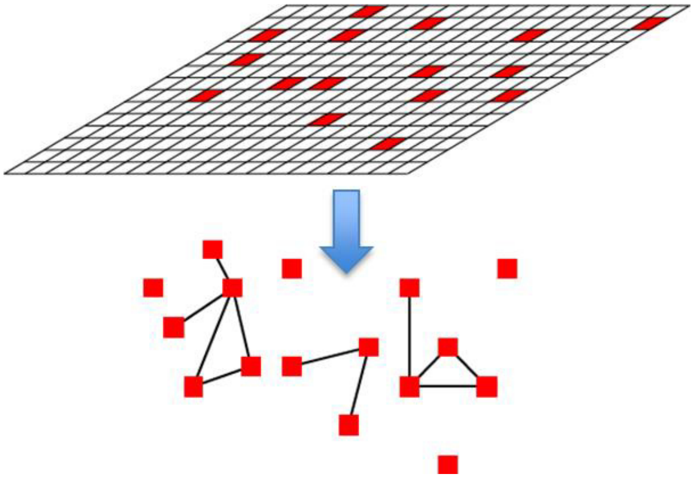


Figure 3: Illustration of interdependencies using graph representation

Then, the potential conflicts are grouped by cells and by flight level in order to identify clusters of potential conflicts that share a physical location in the space. Once the clusters are made, it is distinguished the pairwise conflicts that produces a unique potential concurrence event using time information. This step transforms the spatial representation of the potential conflicts induced by the grid into a A-dimensional representation, see Figure 4.

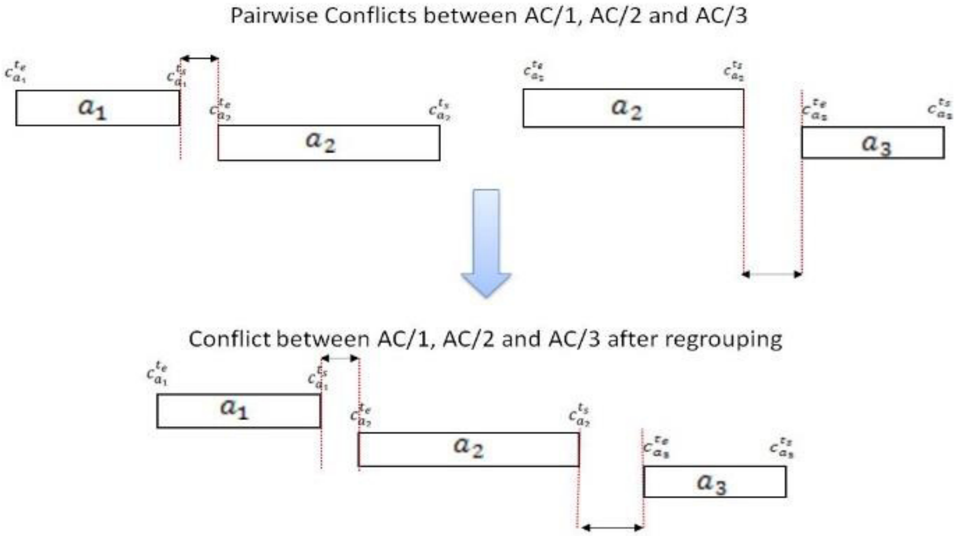


Figure 4: Regrouping two pairwise conflicts to form one conflict node

All the nodes in graph G are outputs of this procedure, thus, one node, which represents one potential conflict, could involve more than one aircraft. Furthermore, two different nodes may represent two potential concurrence events in the same cell, but involving different aircraft in different time.

To construct G it is defined also the edge set $E(G)$. As aforementioned, the edges in G must represent the interdependencies between potential concurrence events and the rescheduled takes-off times. Hence, edges must be related to RBTs of the aircraft involved in the nodes of G. It is addedand edge of uv to $E(G)$ if and only if there is at least one aircraft involved in node u and in node v. That is an edge $uv \in E(G)$ if and only if u and v shares an aircraft.

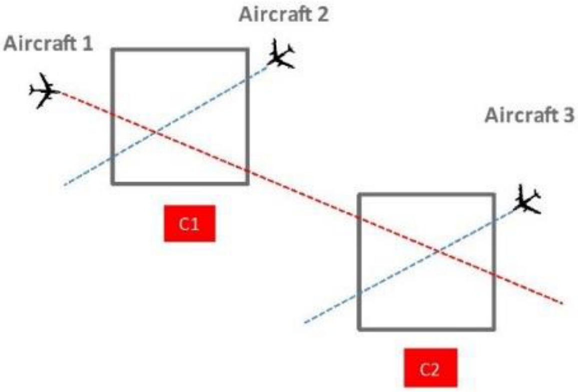


Figure 5: Two potential conflicts shearing aircraft 1

Figure 5 shows two potential concurrence events that occur in different cells. Let be u the node of G that represents the potential conflict listed in cell c_1 and v the node for the conflict in c_2. Then, it is added the edge uv to $E(G)$ because u and v share Aircraft 1.

The problem is represented by taking advantage of the adjacency list and the adjacency matrix. For the traversal graph, also known as graph search, the Depth-First Search (DFS) algorithm is used. By formulating the problem using graph theory, the whole function can be decomposed to find a set of disconnected graphs that form independent clusters, as shown in Figure 6.

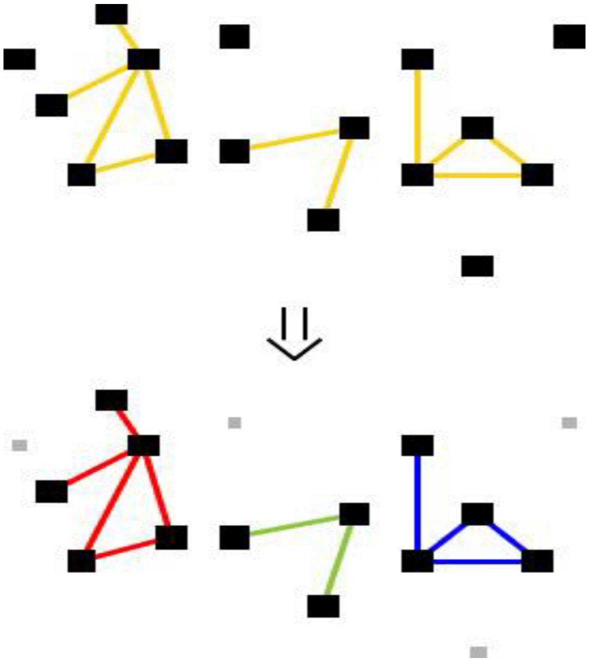


Figure 6: Independent clusters

Moreover, graph representation allows identifying concurrence and coupling interdependencies. Concurrence interdependencies are those which appear between aircraft that are in the same node in G, see Figure 7.

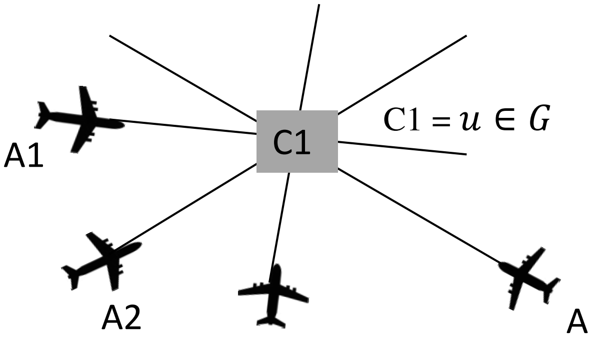


Figure 7: Concurrence interdependencies

If there exist in G a uv-path between two nodes u and v each one encoding a potential conflict, then there is a coupling interdependence between them, see Figure 8.

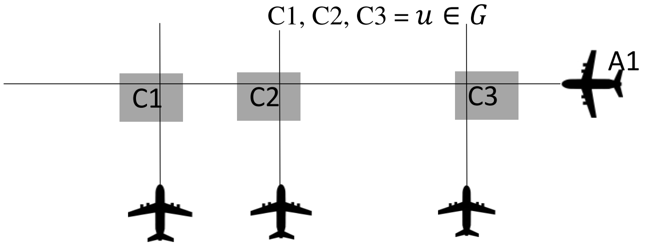


Figure 8: Coupling Interdependencies

The introduction of coupling and concurrence interdependencies allows it to define metrics to understand when an aircraft should be delegated or eliminated of the solution space.

Finally, when rescheduling take-off times, the potential concurrence event encoded in u may result in a reduction of the clearance H in v by modifying the CTOT of Aircraft 1 and vice-versa. In cases where u and v represent potential conflicts with a positive clearance H in both cases, a rescheduling take-off in Aircraft 1 may remove one potential conflict but, produce at same time a real conflict later on. The formulation based on graph theory allows to represent real conflicts and their interdependencies and to visualize the complex structures.

Once the interdependent clusters are detected, the mitigation tool based on constraint programming can be supported. By partitioning the problem size, better computational performance and the reduction of the probability of ATC interventions due to greater clearance times could be achieved, which directly enhances the airspace demand-capacity balance.

2.3 Mitigation Methodology

The mitigation algorithm shall be formulated as an optimization problem where the constraints are formulated to remove the tight interdependencies (H>0). The mitigation tool is based on the following modelling structures.

A set of aircraft
C set of cells that have a concurrence event
F set of Flight Levels

$$C_A^F = \{< c, a, f > \mid \forall c \in C, \forall a \in A, \forall f \in F\} \tag{2}$$

$$RBT_a = \{\hat{g}_i^{a_f}\}, \qquad i = 1..p(a) \tag{3}$$

$$\text{d.v. } \delta_a \in [-\delta_{min}, \delta_{max}], \forall a \in A \tag{4}$$

$$\text{d.v.} P_{c_{a_f}} : sz\left(P_{c_{a_f}}\right) = \left((c_{a_f}^{te} + p_w(t_e)) - (c_{a_f}^{ts} + p_b(t_s))\right), \forall c_{a_f} \in C_{A_F} \tag{5}$$

$$\text{d.v. } O_c = \left\{P_{c_{a_f}} \middle| c_{a_f} \in C_{A_F}\right\}, \ \forall c \in C, \forall f \in F \tag{6}$$

$$\text{d.v. } G_a = [s_a, e_a) \tag{7}$$

$$\text{d.v. } g_i^{a_f} = [\mathrm{s}(g_i^{a_f}), e(g_i^{a_f})\big), \forall a \in A, \forall f \in F, \forall i \in 1..p(a): \quad sz(g_i^{a_f}) \in [sz(\hat{g}_i^{a_f}) - l(\hat{g}_i^{a_f}), sz(\hat{g}_i^{a_f}) + l(\hat{g}_i^{a_f})] \tag{8}$$

$$\text{d.v. } T_a = \left\{g_i^{a_f} \mid \forall a \in A, \forall f \in F, i \in 1..p(a)\right\} \tag{9}$$

Minimize:

$$w_1 \sum_{a=1}^{n} |\delta_a| + w_2 \sum_{a=1}^{n} L(G_a) \tag{10}$$

subject to:

$$s\left(P_{c_{a_f}}\right) = (c_{a_f}^{ts} + p_w(t_s)) \pm \delta_a \tag{11}$$

$$\forall P_{c_i}, P_{c_j} \in O_c \quad NO(O_c) \Leftrightarrow \pi(P_{c_i}) < \pi(P_{c_j}) \Rightarrow e(P_{c_i}) \leq s(P_{c_j}) \tag{12}$$

$$s(G_a) = CTOT_a \pm \delta_a \tag{13}$$

$$e(G_a) \in [TTA_a - 1, TTA_a + 1] \tag{14}$$

$$span\left(G_a, \{g_i^{a_f}\}\right), \forall a \in A, \forall g_i^{a_f} \in T_a \tag{15}$$

$$\forall a \in A, \forall f \in F, \forall i, j \in 1..p(a)$$

$$NO(G_a) \Leftrightarrow \pi(g_i^{a_f}) < \pi(g_j^{a_f}) \Rightarrow e(g_i^{a_f}) \leq s(g_j^{a_f}) \tag{16}$$

$$e\left(g_i^{a_f}\right) \leq s\left(g_j^{a_f}\right), \forall i, j\colon i < j \tag{17}$$

$$e\left(g_i^{a_f}\right) = s\left(g_j^{a_f}\right), \forall i, j\colon j = i + 1 \tag{18}$$

$$\begin{cases} s\left(g_i^{a_f}\right) = s(P_{c_{a_f}}) \\ e\left(g_i^{a_f}\right) = e(P_{c_{a_f}}) \end{cases} \Leftrightarrow \begin{matrix} s\left(\hat{g}_i^{a_f}\right) = c_{a_f}^{ts} \\ e\left(\hat{g}_i^{a_f}\right) = c_{a_f}^{te} \end{matrix}, \forall c_{a_f} \in c_{A_F} \tag{19}$$

$$synchronize\left([g_i^{a_{f_i}}], \left\{g_i^{a_{f_j}}\right\}\right), \forall g_i^{a_f} \in T_a \tag{20}$$

The CP model data structure defines a set of aircraft A and a set of concurrence event cells C at a given flight level F.

The decision variables ensure that the departure adjustment of the aircraft remains in the defined timeframe of [-5,10] minutes (equation 4); the interval for the occupancy of the cell c by an aircraft a at a given FL f with its size and start and end time (equation 5); each of the cells can be occupied by one aircraft at a certain FL at a time, so the aircraft going through the cell must be sequenced accordingly (equation 6); the representation of the entire flight trajectory where s_a will be the take-off time and e_a the arrival time in the solution (equation 7); the interval variables representing the segments of the G_a and their size (equation 8); and the sequence variable T_a is introduced to set the relationship between the trajectory segments g_i^a and the entire trajectory G_a (equation 9).

The bi-objective optimization goal that combines the aspects w_1 (minimizing the total aircraft delays) and w_2 (binding the Target Time (TT); where a refers to the aircraft, δ_a is the delay applied and $L(G_a)$ represents the minimization of all RBT segments according to their allowed elasticity if the TT cannot be met), see equation 10.

The first constraint aims to model the shifting of every interval variable $P_{c_{a_f}}$ according to the applied delay and its time-uncertainty (equation 11). Furthermore, all aircraft in a cell c with proximate events should have no overlap (equation 12). The interval variable G_a which represents the duration of the flight is determined by the constraint of the take-off time (equation 13) and the time of arrival (equation 14). Furthermore, the relationship between the flight interval variable and its segments is modelled by the following *span* condition to ensure the completeness of the trajectory (equation 15). The constraint *span* states that the interval flight spans over all present intervals from the set segments. That is, interval flight G_a starts together with the first present segment interval and ends together with the last one. To ensure this, the *no overlap* constraint (equation 16) ensures that interval variables to not overlap each other. In this case, the individual Reference Business Trajectory (RBT) segments should have no overlap. Also, the constraint is added that ensures that one segment has to start before the next (equation 17) and that the start of segment j takes place after the end of segment i (equation 18). Equation 20 is used to link the interval variable $P_{c_{a_f}}$ that is used in combination with the sequence variable O_c to remove the concurrence events at cell c, with the concurrence segments of the trajectory T_a, since they are representing the same time windows. Finally, (equation 20) synchronizes the trajectory segments of different FLs to model the 3D concurrence event mitigation. (Schefers et al. 2016)

3 APPLICATION AND EXPERIMENTAL RESULTS

The developed methodology has been applied to a testing case. First, it is shown the operational environment and operational context considered for the experiments. Secondly, the testing case framework is outlined. Lastly, the section presents and discuss the obtained results.

3.1 Service in a TBO Scenario

The methodology has been designed to be executed as a recurrent service that takes benefits of the Trajectory-Based Operations concept, in which the AUs intentions are available to all interested parties (Figure 9). The input of the service is a set of reference trajectories that represent the instantaneous predicted S-T distributions of flights (on ground and on air) that crosses the target sector. These trajectories are then used to detect, analyse and mitigate the concurrence events. The output of the service is a set of more effective ETOTs that mitigate the detected concurrence events. The service is then iteratively executed to obtain the latest predicted information of the reference trajectories.

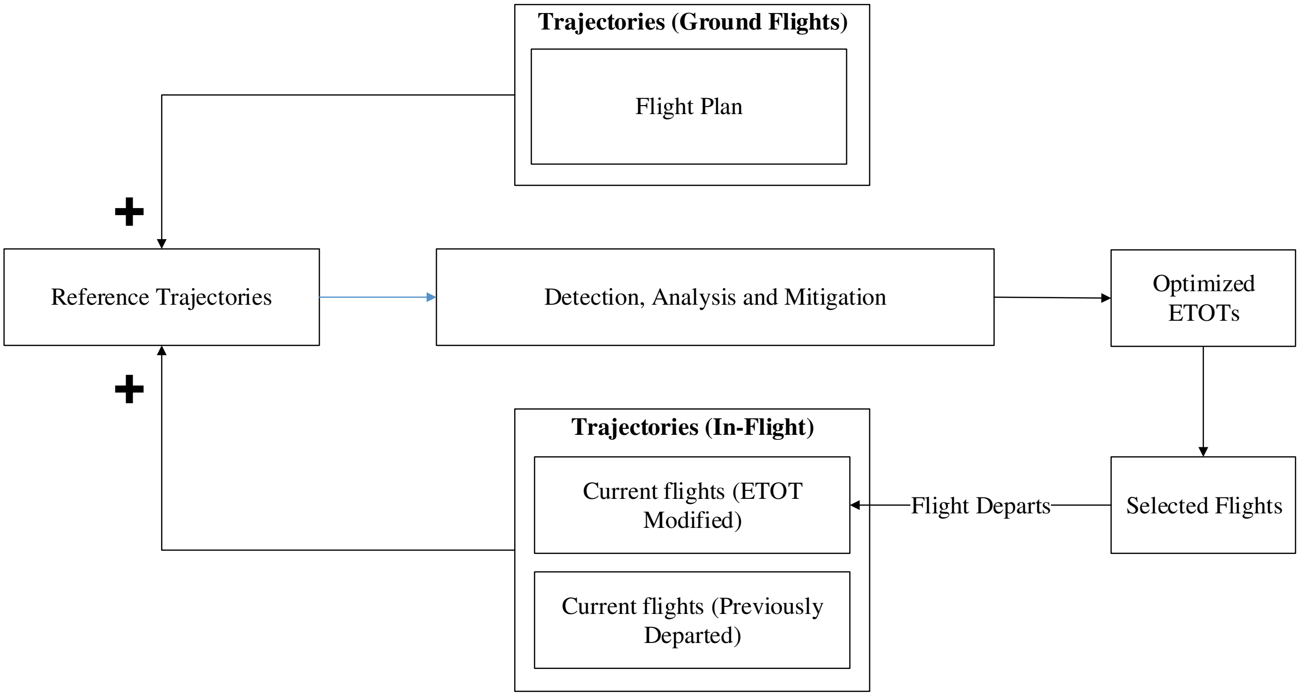


Figure 9: Recurrent Service

The tuning of the mitigation parameters is based on operational concerns: The look-ahead parameter L ensures that the trajectory view of the flights within the mitigation domain goes beyond the sector. The ATC reaction time t_{ATC} ensures feasibility of taxi out operations.

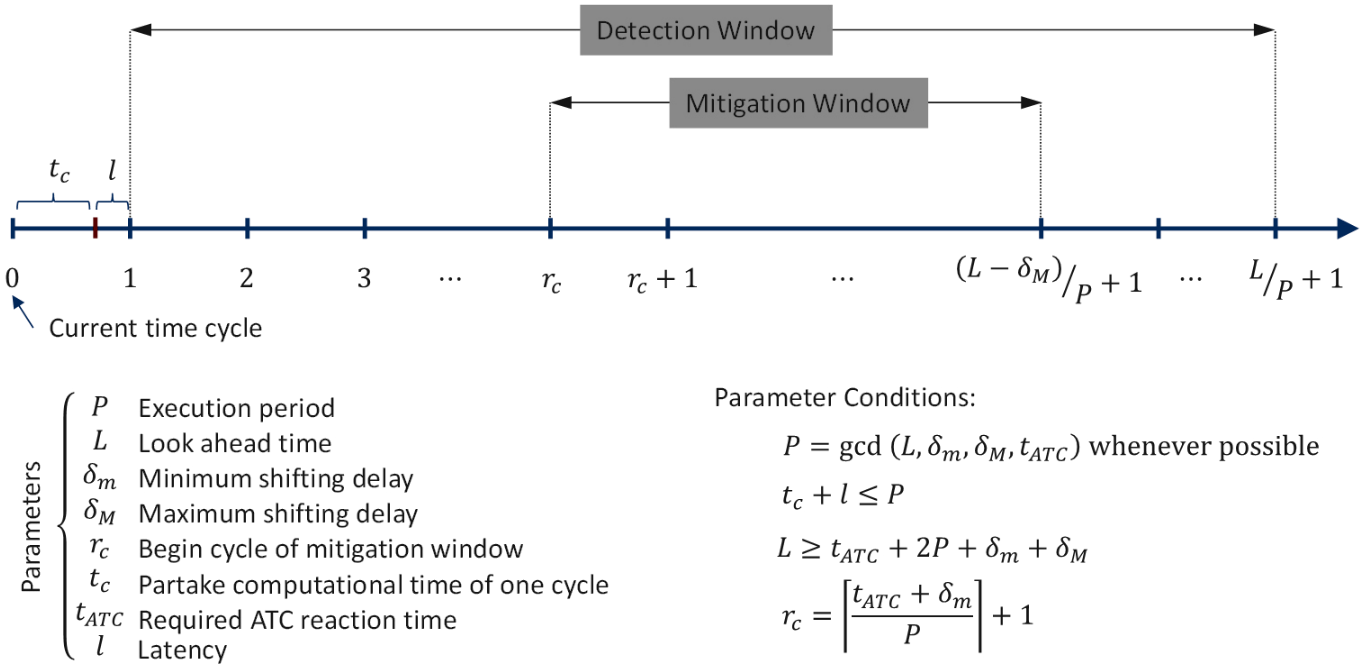


Figure 10: Service definitions

The following terms are defined for understanding the main variables and parameters (all in minutes) of the execution timeline (Figure 10):

- Execution Period (P): time period between consecutive executions.
- Look-ahead time (L): is evaluation period for detecting potential concurrence events among trajectories that are active during this period. It starts at cycle 1 (current time plus P)
- Cell-size (S_C): it is the size of the cell c.
- Shifting domain: ($[\delta_m, \delta_M]$): minimum and maximum delay that can be applied to the ETOT.
- Offset: is the along track deviation present in a trajectory with respect to the original RBT. It can be caused either by an action (applied shifting delay) or by actual flying conditions.
- Required ATC reaction time (t_{ATC}): is the minimum time window between the time the ATC is informed about a possible departure shifting and the new assigned ETOT.
- Detection Window: timeframe where detection algorithm applies. It starts at current time plus P and ends L minutes later.
- Mitigation Window: is the time frame where departures are considered for mitigation actions. It starts at current time plus $r_c P$ and ends $L - \delta_M$ minutes later. Note that trajectories departing between $((L - \delta_M)/P) + 1$ and $(L/P) + 1$ intervals are considered for detection but not for mitigation.
- Minimum Clearance: it is the time in minutes of the minimum clearance to consider a potential concurrent event as a real conflict.

The following concepts are also introduced:

- Selected Airports: set of stations that are coordinated by the algorithm.
- Detection domain: all traffic that exists within the look-ahead time.
- Mitigation domain: all the flights whose departure is within the mitigation window in a given execution cycle and which depart from Selected airports.
- Controlled domain: set of flights departing from selected airports and whose departures have been regulated by actions at a given execution cycle. Once a flight becomes a member of this set it cannot belong to the mitigation domain in future execution cycles.

The detection domain represents all traffic that exists within the look-ahead time (L). The mitigation domain represents all the flights whose departure is within the mitigation window in a given execution cycle from one of the selected airports.

It is assumed that no uncertainties are present in space nor in time. Further analysis of the methodology under real uncertainties conditions for ground operations or during flight is part of the future work of this project. At this point, we assume that the input reference trajectories represent high-adherence to the nominal routes and the trajectories are flown as described in the traffic scenario.

When the cell-size increases, the uncertainties are reduced. Similarly, when the look-ahead time increases it is expected that the uncertainty level increases. Therefore, the effectivity of the methodology depends, among other factors (e.g. traffic or number of selected airports), on the *cell-size* (S_C) and *look-ahead time* (L) parameters. In an operational scenario, it is expected that these values are fine-tuned depending on the traffic conditions and the uncertainty levels that are expected for the solution.

3.2 Case of Study London TMA

The London Terminal Maneuvering Area (LTMA) is a complex Multi-Airport System (MAS) (CAPITA 2013). In 2015, it handled 155.2 million of passengers and received more than 1.05 million of flights (CAA 2017).

LTMA traffic follows inbound and outbound nominal routes to/from the five main airports (Stansted-EGSS, Luton-EGGW, Heathrow-EGLL, Gatwick-EGKK and City-EGLC, see Figure 11). Some of these routes include alternative procedures in case of technical disruptions of navaids or depending on the runway configuration (NATS 2017).

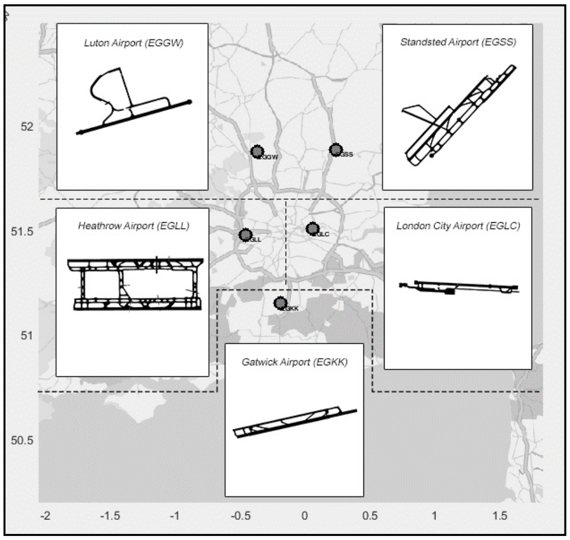


Figure 11: London Terminal Maneuvering Area (LTMA) Airports

For a sample of trajectories, it has been calculated the number of flights that crosses the most relevant waypoints of the TMA. Figure 12 represents the waypoints areas with higher density in the LTMA: Brooksman's Park (BKP), Lambourne (LAM) and Compton (CPT) waypoints located at the North, North-East and North-West of London Heathrow Airport (EGLL), respectively.

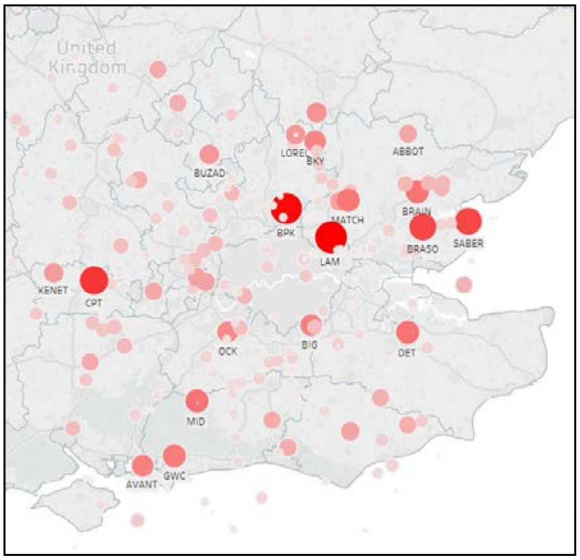


Figure 12: High-density areas in London terminal airspace (data adopted from Eurocontrol DDR2 (Eurocontrol 2017)**)**

The Capital sector (EGTTCAP), represents an often-regulated area of the London TMA. EGTTCAP is the result of *band boxing* the elementary volumes Compton (EGTTCPT) and Vaton (EGTTVAT). Figure 13 shows the hourly demand distribution of EGTTCAP. Regulations highlighted in red have been triggered in EGTTCPT.

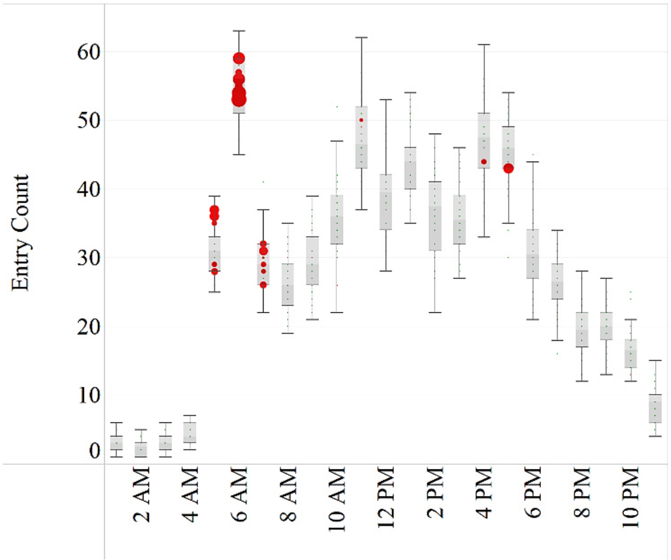


Figure 13: Regulations in Capital (EGTTCAP) during summer 2016 (Eurocontrol 2018a)

Departure from the LTMA is often limited by the so called Minimum Departure Intervals (MDI). The application of MDI rules involves that target airports (e.g. Stansted or Birmingham) are required to limit successive take-offs for a specific interval of time on the same SID (e.g. one flight each ten minutes). The rule aims at regulating the number of aircraft on air due to an unexpected increase on the entry-count of highly congested sectors. The problems associated to these rules is that their application targets all the departures on the same SID. This effect produces that some flights in the departure queue could be affected but they do not cross the congested volumes.

The idea of using the methodology is to determine a more efficient and logical departure sequence, *targeting only the flights that could produce concurrence events,* resulting in a more favorable demand distribution in the congested sectors. The ultimate goal is then reducing the number of ATC interventions in the *air* helping to maintain the LTMA airports throughput.

The algorithm presented in this paper was applied as a service to different realistic traffic samples obtained from Eurocontrol Demand Data Repository (DDR2) (Eurocontrol 2018a). Data provides a very accurate picture of pan-European air traffic demand, from several years ahead until the day before operations. It can be used to support the network collaborative planning process that include strategic, seasonal and pre-tactical planning as well as for the planning of special events or major ATM evolution projects.

Simulation exercises have been designed using the full LTMA volume (EGTTTC) to analyze and study optimal working conditions for the proposed methodology. Firstly, a traffic scenario was selected to analyze the three most relevant parameters: cell size, number of airports in operation and look-ahead time. Once the appropriate operating parameters from this scenario are identified, they are applied to other days/times of traffic.

To test and evaluate the method towards the most relevant operating parameters, a variety of experiments using the developed framework were tested in a fast simulation exercise, see Table 1. The simulation reflects upon the output of each module which is:

- **Detection:** number of potential concurrence events that could be removed.
- **Analysis:** number of clusters within the mitigation window
- **Mitigation:** number of removed potential concurrence events in the cycle together with the number of applied shifting.

The experiments 1-10 test the influence of the cell size towards the percentage of CE that can be mitigated using the proposed methodology. The cell size (S_C) ranges from 2NM to 6NM. Also, the impact of implementing the methodology in 2 or in 4 operating airports that supply the LTMA was analyzed. We have chosen a 2-airport and 4-airport experiment setup based on preliminary observations of the traffic. The two main airports that feed traffic to the EGTTCAP sector are London Luton (EGGW) and London Stansted (EGSS). Additionally, Birmingham (EGGD) and Bristol (EGBB) airports feed an important amount of traffic to EGTTCPT. Experiments 11-16 analyze the look-ahead time, considering the service definitions as explained in Figure 10. Furthermore, an analysis of the variability of the entry-count with respect to the cell size and an analysis of the relationship between the occupancy and the CE was performed to obtain information at an aggregated level regarding the system's sensitivity to network dynamics.

	Cell Size					Airports		Look-Ahead Time (L)		
Experiment	2NM	3NM	4NM	5NM	6NM	2	4	45	60	75
1	✓					✓			✓	
2		✓				✓			✓	
3			✓			✓			✓	
4				✓		✓			✓	
5					✓	✓			✓	
6	✓						✓		✓	
7		✓					✓		✓	
8			✓				✓		✓	
9				✓			✓		✓	
10					✓		✓		✓	
11	✓					✓		✓		
12	✓					✓			✓	
13	✓					✓				✓
14		✓				✓		✓		
15		✓				✓			✓	
16		✓				✓				✓

Table 1: Performed experiments to demonstrate the behavior of the methodology according to identified parameters

The parameters used in the fast simulation consider a rolling horizon with a cycle repetition (P) of every 5 minutes, a required ATC reaction time (t_{ATC}) of 10 minutes, and the mitigation CTOT window of [-5, 10] minutes.

3.3 Experimental results

As an initial step, a traffic scenario was selected to perform the fast simulation and to provide recommendations about the most relevant operating parameters: cell size, number of operating airports and look-ahead time. It was used a sample traffic data of 19th of July 2017 from 6am to 7am. LTMA has been the target of an important number of regulations during summer of 2017 (including the 19th of July 2017), and most regulations occurred in the traffic peak period between 6:00am and 7:00am (Eurocontrol 2017).

The experiments mentioned above in Table 1 are performed to understand the systems behaviour with respect to the most relevant operating parameters. Later, these findings are compared and applied to other traffic scenarios to consolidate the results and generate a benchmark.

A graphical visualisation of the trajectories of chosen scenario is shown in Figure 14. The red lines indicated trajectories with CEs whereas the green lines indicate a CE-free trajectory during the indicated timeframe. The white geometric shapes surrounding the London area show the extent of the LTMA.

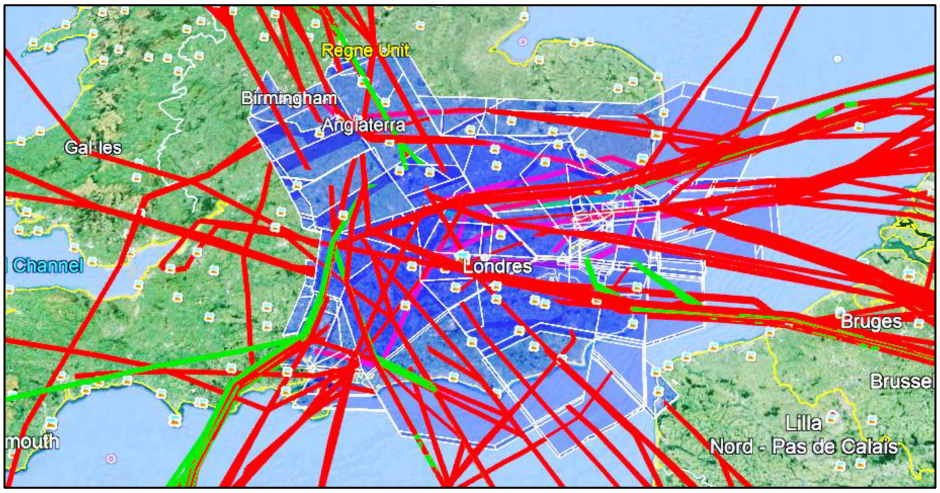


Figure 14: Visualization of the RBTs of the selected traffic scenario

In the selected scenario, an average of 16% of CE belongs to the solution space of the algorithm (in the following indicated as PCEs), meaning that the trajectories are flights that are still on the ground, belongs to one of the airports that are considered and therefore can be time-shifted by the mitigation process. The percentage in Figure 15 indicates that for this traffic scenario the algorithm could apply mitigation rules in 16% of the traffic (at maximum) in order to reduce the amount of potential ATC tactical interventions on air.

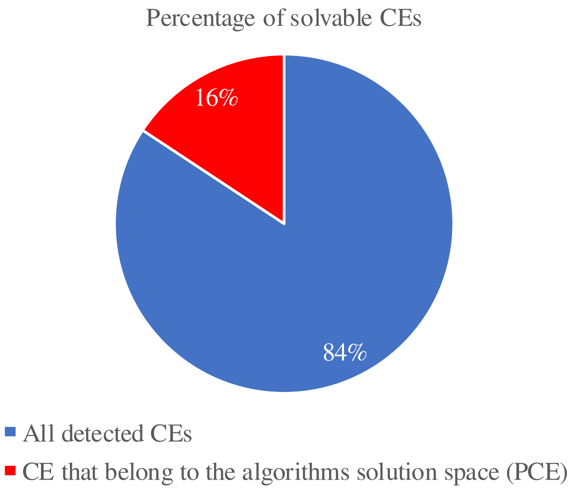


Figure 15: Percentage of overall detected CEs and those that belong to the algorithms solution space (PCEs)

Figure 16 presents the amount of PCEs and CEs that have been detected. With an increased cell size, the number of CEs and PCEs increase because more aircraft share a cell and therefore more flights are considered CEs. The amount of PCEs is directly proportional to the number of selected airports where the mitigation process is applied. The 84% of concurrence events that does not belong to the algorithm solution space are produced by flights that departed from airports outside of the London area.

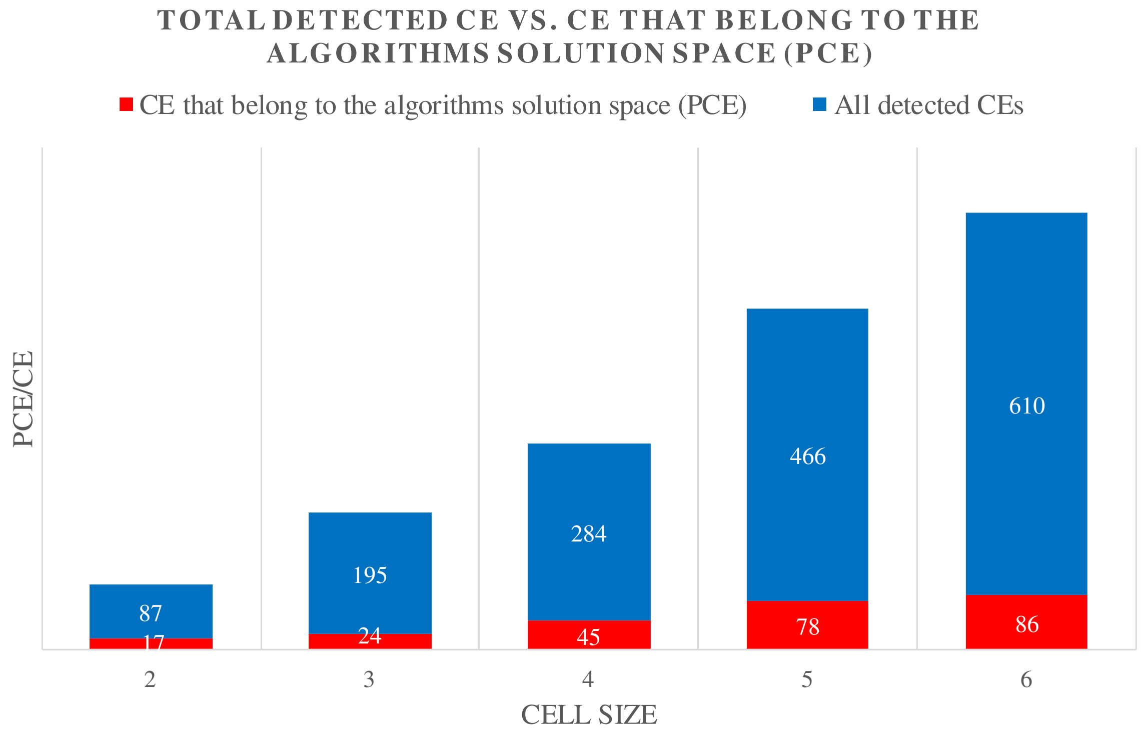


Figure 16: Total detected CE and PCEs according to the applied cell size

The most remarkable result to emerge from the **analysis of the cell size** (experiments 1-10, Table 1) is that the percentage of solved PCEs and the absolute number of solved PCEs is maximum for cell size of 2 and 3 NM. Starting from a cell size of 4NM, the solvability decreases significantly as show in Figure 17. Since LTMA is a very dense area with a high volume of traffic and many S-T interdependencies exist, there are cases when there is not enough capacity in the temporal dimension to change the ETOT without producing downstream effects. However, the number of CEs that cannot be solved during mitigation is very low using a cell size of 2 or 3 NM (Figure 17). The percentage of solved PCEs reaches almost 90% with a cell size of 2NM and 75% with a cell size of 3NM (grey line). Furthermore, when looking at the absolute numbers of PCEs that have been solved (orange bar), the highest number of PCEs are solved applying a cell size of 2NM (15 CEs) and 3NM (18 CEs). This result furthermore shows that the percentage of overall solvable CEs (green bar) increases with a bigger cell size until it achieves a saturation level at which no more concurrence events are detected.

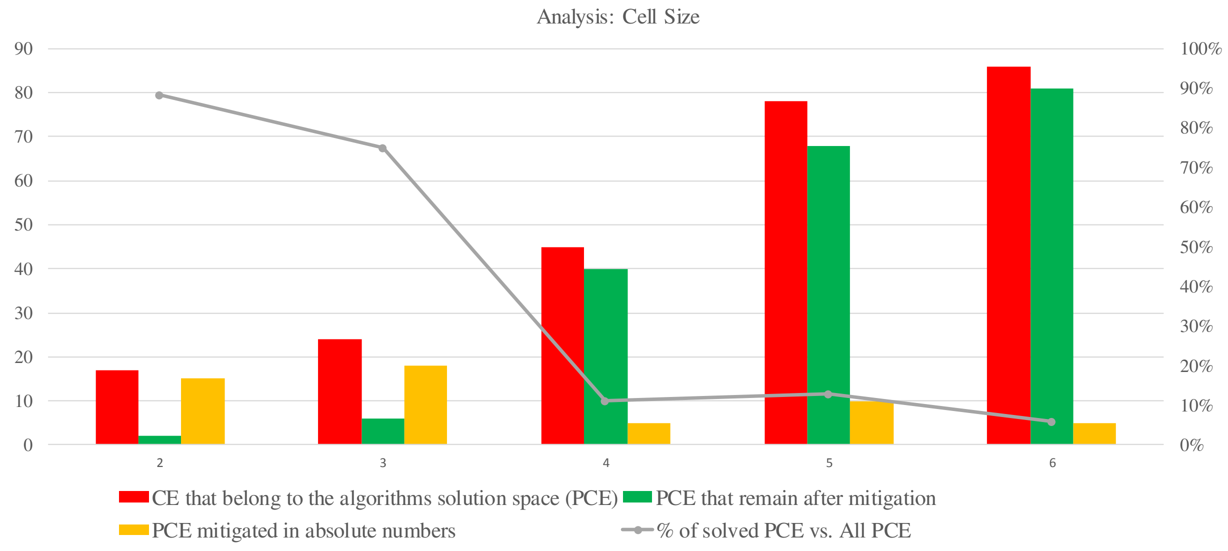


Figure 17: Analysis of the cell size. The red bar indicates the amount of CE that can be considered by the algorithm (PCE). The green bar indicates the amount of PCE that could not be removed. The grey line shows the percentage of solved PCEs with respect to all PCEs and the orange bar shows the mitigated PCEs n absolute numbers.

Furthermore, to obtain information at an aggregated level regarding the system's sensitivity to network dynamics, an analysis of the effect of the cell size on the occupancy has been performed. As it can be seen in Figure 18, all three parameters, entry-count, exit-count and occupancy remain almost constant while the cell size increases. The constant values throughout the different cell size is an indicator that all trajectories are detected independent of the cell size is.

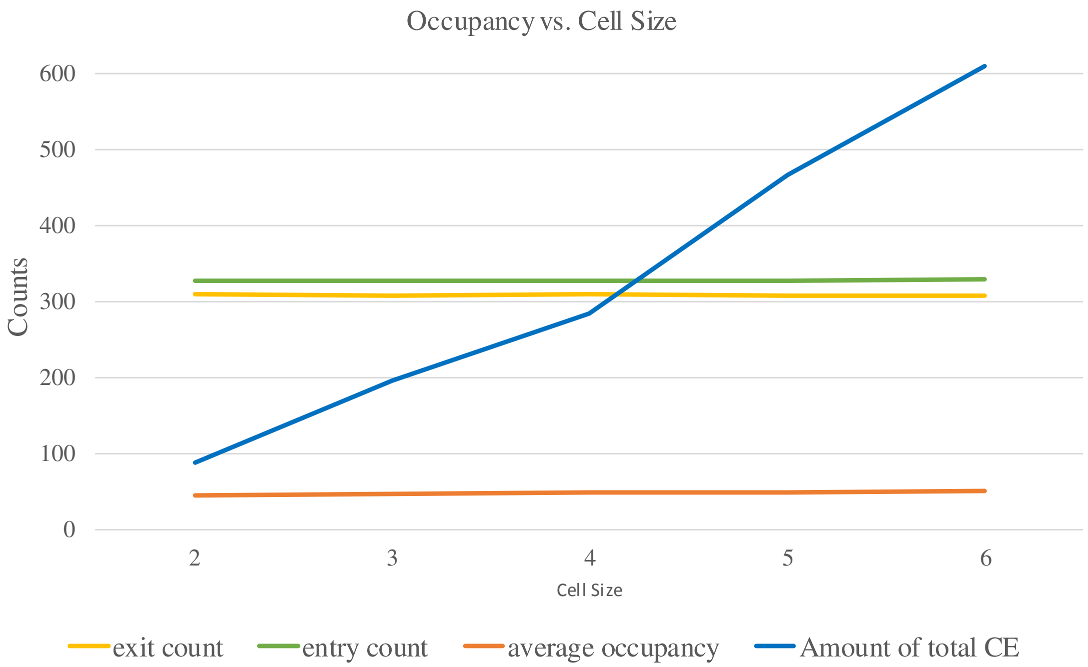


Figure 18: Occupancy vs. Cell Size. It can be seen that the entry and exit counts and the occupancy remain stable with an increasing amount of CE.

The second parameter to analyze is **the number of operating airports**. The number of CE using either 2 (EGGW and EGSS) or 4 airports (EGGW, EGSS, EGBB and EGGD) seems not to influence significantly on the mitigation possibilities for small cell sizes. When the cell size increases, the difference between 2 or 4 operational airports increases and in the case of 6NM, 17 more CE could be solved, see Figure 19. The reason for this is that for the sample of the experiment, EGGW and EGSS provide higher traffic volume than EGBB/EGGD.

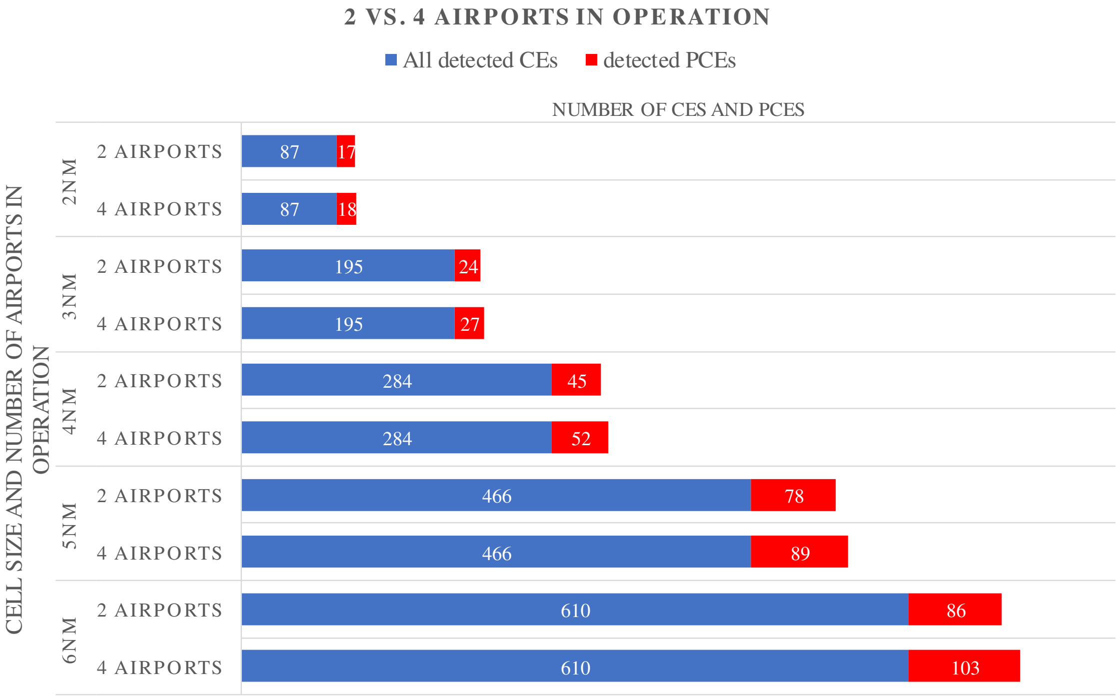


Figure 19: Comparison of CEs with 2 operating airports and 4 operating airports

The third important operating parameter that has been analysed in the **look-ahead time** (experiments 11-16, Table 1). For these experiments, a series of different look-ahead times were tested to understand their influence on the amount of concurrence events. It is assumed that the possibility of CEs is lower with a smaller look-ahead time and grows as we increase it until a saturation level is reached. On one hand, with a very small look-ahead time the effectiveness of the method to solve CEs is very small and on the other hand, a big look-ahead time causes an increase of the uncertainty. Therefore, the analyses should reveal which look-ahead time has the best trade-off between effectiveness in solving CEs and uncertainty.

The smallest look-ahead time that has been chosen is 45 minutes. As explained Figure 10, there are various parameters to determine the look-ahead time. The *look-ahead time* is the time that trajectories are predicted in advance. Usually, this time is calculated according to the average time of an aircraft inside the TMA, which in this case is around 20 minutes. The *ATC time* is the time, the ATC need to react to provide the ETOT without being affected by ground operations. This parameter depends on different factors such as the skills of the ATC to match the proposed ETOT, the airport layout and/or the airport traffic/demand.

Finally, the *execution time* is the time needed to execute the algorithm. In this case, the execution time is multiplied by two (2), first to execute the algorithm and second to take into consideration the latency to submit the solution to the ATC. Therefore, for this simulation configuration the smallest look-ahead parameter is 20 min. (look-ahead time) + 15 min. (ATC time) + 5 min + 5 min (execution time) = 45 min. Note that the uncertainty associated to the first 15 minutes is expected to be absorbed at tactical level by the ATC capabilities to take-off the aircraft on the proposed ETOT. A sensitivity analysis is required to estimate the take-off time accuracy required to tackle the uncertainties associated to the trajectory until intercepting the concurrence event zone.

The test revealed that there was a correlation between the look-ahead time parameter, the cell size and the execution time of the algorithm. The execution time increased according to the look-ahead time parameter applying a cell size of 2 NM, whereas the execution time with 3NM seems to grow with a lower rate, see Figure 20. The reason of this difference in that the time execution is related to the trajectory discretization and the amount of data the algorithm need to process to achieve a valid solution.

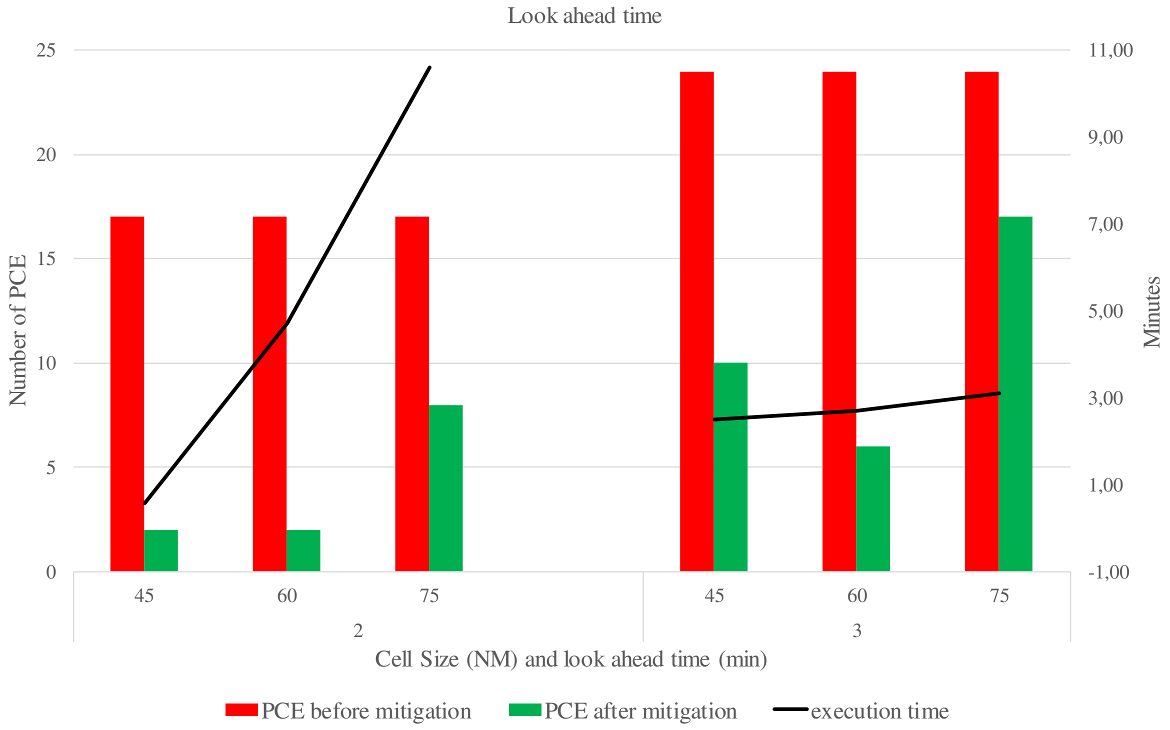


Figure 20: Analysis of the look-ahead time parameter.

The number of PCE before mitigation remains equal through all experiments, which is a positive indicator that the algorithm is capable to identify all CEs and PCEs of the selected traffic sample. The number of PCEs increases significantly applying a look-ahead time greater than 60 minutes.

Finally, for an improved visualization of the effectiveness of the tools, a graphical illustration shows the reduction of the CEs before and after mitigation for the selected case. The chart in Figure 21 shows the PCEs from the traffic scenario using a cell size of 2NM, a look-ahead time of 60min and considering 2 operating airports. A total of 88% of the PCEs are solved (meaning that from 100% of concurrence events that could have been solved, 88% were solved), which represents the 20% of the total CEs (the 88% of solved PECs represent 22% of all flights).

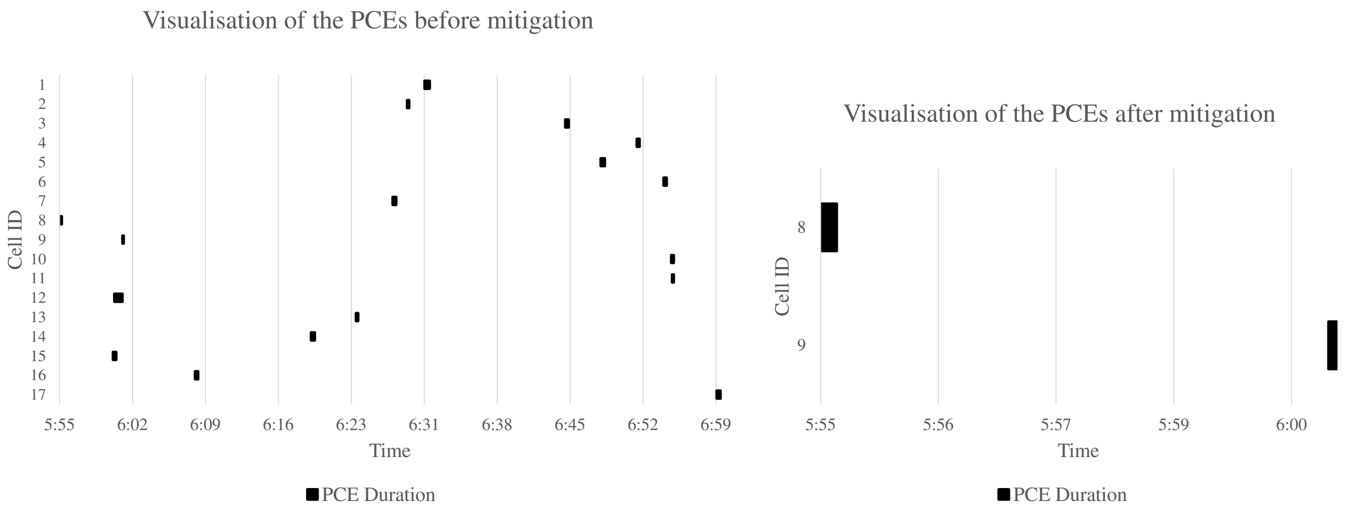


Figure 21: Visualization of the PCEs. The Gantt chart shows the PCEs before mitigation and after mitigation. A total of 88% of the PCEs is solved, making it 20% less probable that there is an ATC tactical intervention.

In summary, a first recommendation for operating parameters can be retrieved from these experiments. Considering the scenario of this study case, the cell size should be set to 2NM or 3NM (depending on the available performance resources) the difference between operating the algorithm at 2 airports or 4 airports in this case becomes significant with a larger cell size whereas the difference between resolved concurrence events is rather small at a lower cell size. Finally, a 60-minutes look-ahead time achieves the best results applying a cell size of 3NM.

A second set of experiments have been carried out using the recommended operating parameters. The traffic samples have been chosen to cover a wide range of demand values (e.g. day of the week and hour of operation). A summary of the tested realistic traffic scenarios is presented in the Table 2.

Day of traffic scenario	Date of traffic scenario	Hour of traffic scenario
Monday	17th of July 2017	6am to 7am
Monday	17th of July 2017	4pm to 5pm
Wednesday	19th of July 2017	6am to 7am
Wednesday	19th of July 2017	4pm to 5pm
Saturday	22nd of July 2017	6am to 7am
Saturday	22nd of July 2017	4pm to 5pm

Table 2: Realistic traffic scenarios that were chosen for the experiments

The experiments revealed that, on average, there are more PCEs that could be solved in the later afternoon, see Figure 22. On Wednesday afternoon and on Saturday afternoon, the number of PCEs that could be solved reaches from 41% to 52%, meaning that in the latter half of the existing total CE could be solved by the proposed algorithm, reducing the possibility of an ATC intervention by over 50%.

During the morning hours, the traffic volume increases because air traffic is building up around the airports. As the demand increases, the air-traffic controllers delay flight departures and take longer to sequence arriving flights. For time slots where no such regulations are applied and a normal daily routine is performed, more possible CEs can be detected and a greater number of CEs can be mitigated.

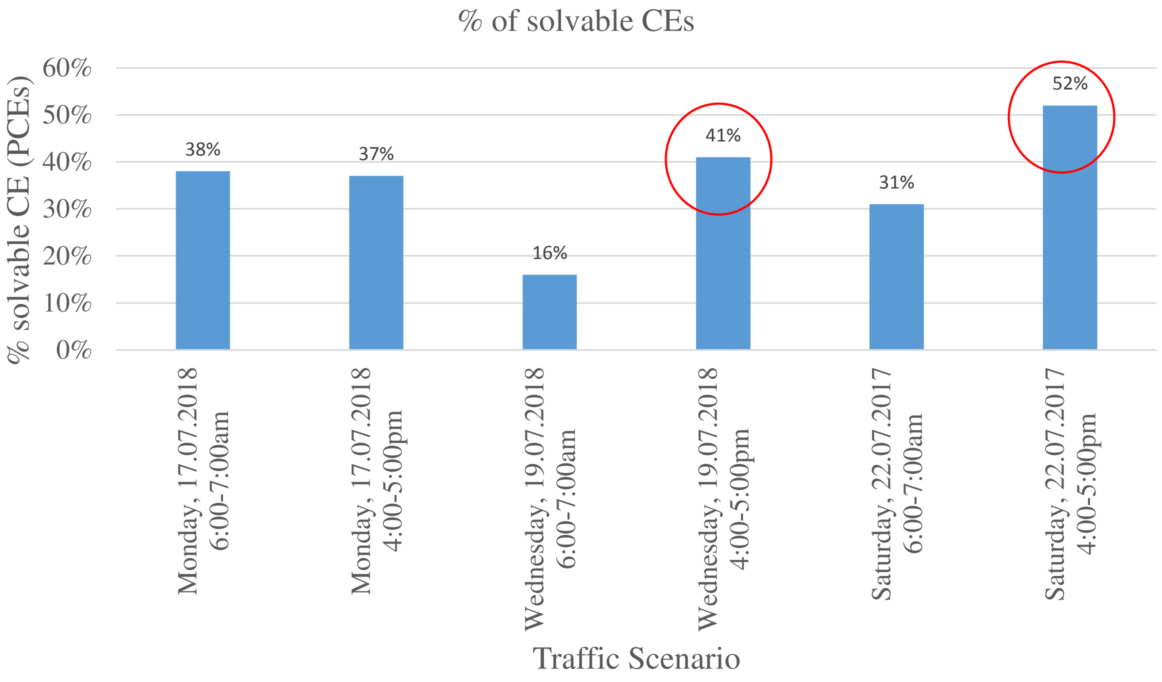
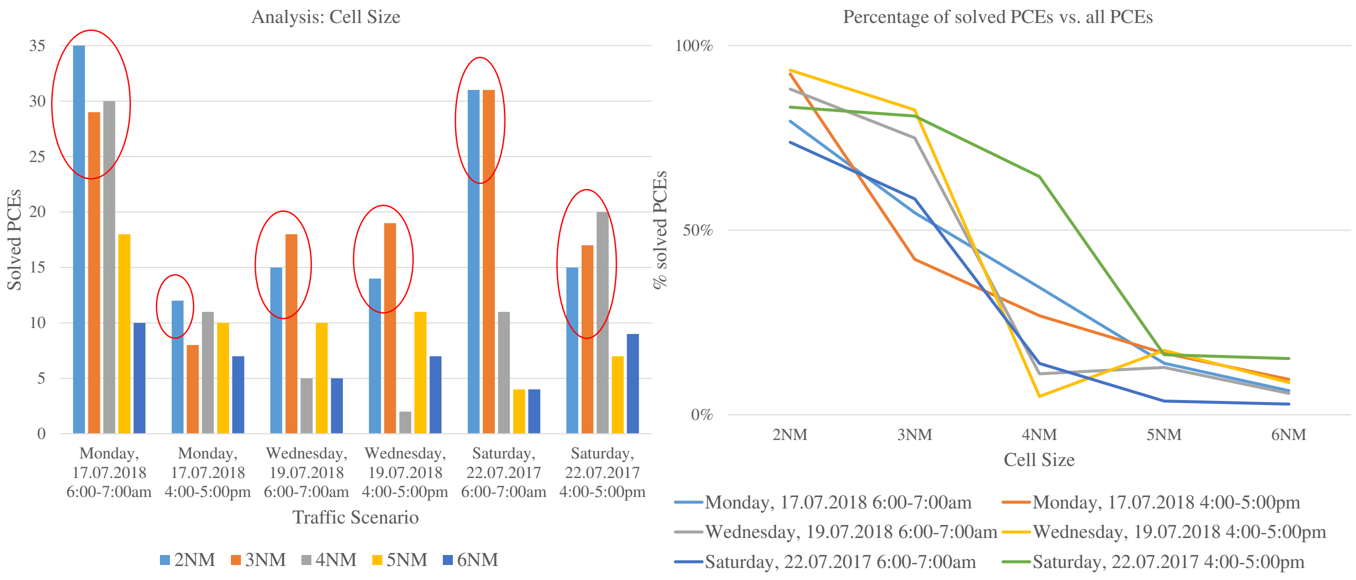


Figure 22: Percentage of solvable CEs (PCEs). The highest number of PCEs that could be solved is observed in the later afternoon hours whereas busy morning hours such as Wednesday morning provide less possibility to solve CEs.

Further tests carried out to determine the most effective **cell size** (S_C) for the parameter confirmed our initial findings. The results on the cell size experiments are represented in Figure 23. The figure shows a clear trend that the absolute number of solved PCEs is higher when applying a cell size of 2NM or 3NM whereas a cell size of 5NM or 6NM solves less PCEs.

Applying a cell size of 4NM, some outliers can be observed. In some cases, the cell size of 4NM solved many CEs whereas in other cases the results are unsatisfactory. Although the aircraft are separated with the determined safety distance, in a real context where the operations involving safety factors tends to be more conservatively, a distance of 2NM might not help to prevent a ATC intervention. Therefore, it is proposed the use of a cell size of 3NM as it gives steady good results throughout all experiments.



(a)

(b)

Figure 23: Summary of results of the analysis cell size. (a) It can be observed that a smaller cell size leads to more solved CEs whereas a larger cell size resolved less CEs in absolute numbers. (b) The percentage of solved PCEs reveal similar results. A smaller cell size leads to more solved CEs and a bigger cell size to less solved CEs. The cell size 4NM is streaked by outliers.

The results of the traffic scenarios with respect to the analysis of the number of operating airports can be seen in Figure 24. The numbers shown below were calculated using the mean of all traffic scenarios. The findings confirm previous results that the difference of the number of PCEs is rather low operating in 2 or in 4 airports, however, contrary to expectations, for these experiments, these values remain low.

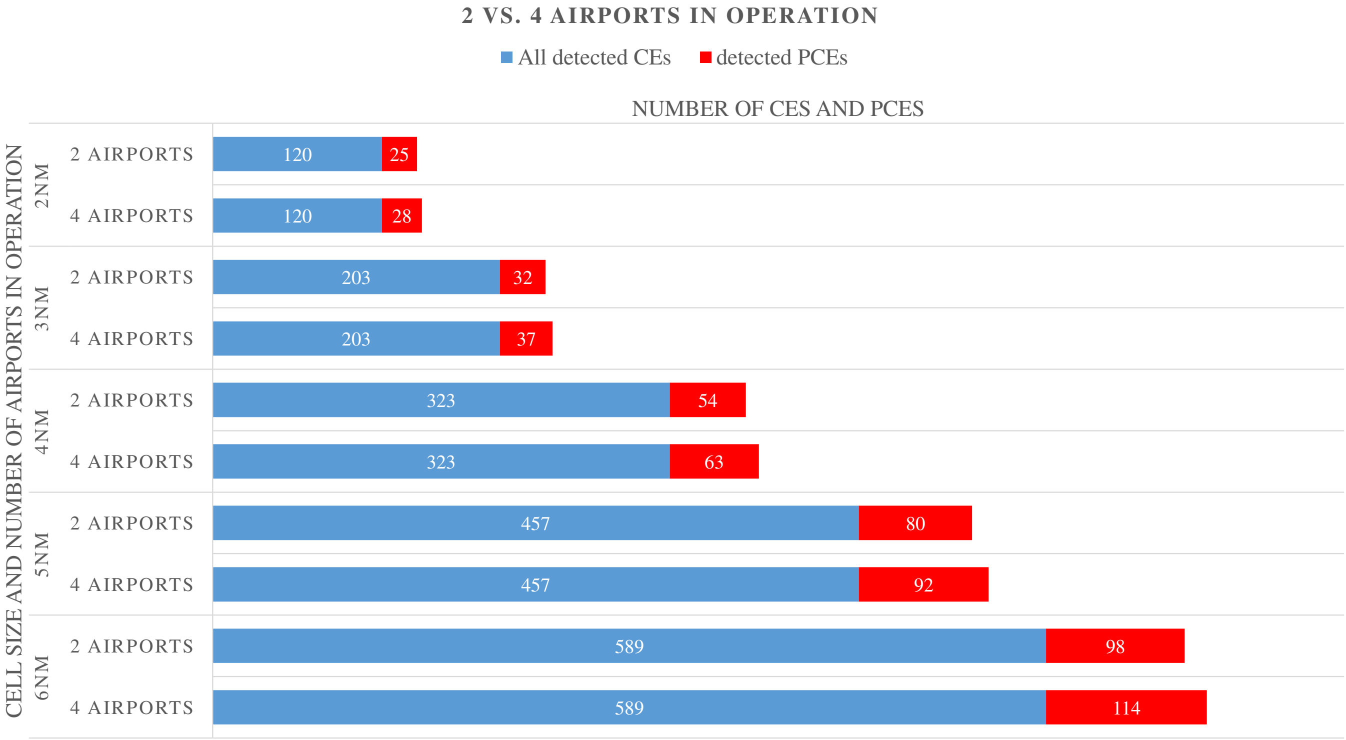


Figure 24: Summary of results for operating in 2 or in 4 airports. The difference of detected PCEs is rather low.

Finally, the analysis of the look-ahead time shows a steady, low amount of non-solvable PCEs after mitigation applying a cell size of 2NM. Moreover, the execution time of the problem grows exponentially with the look-ahead time. In comparison with the cell size of 2NM, applying a cell size of 3NM cell size, shows more non-solvable PCEs after mitigation. Furthermore, the number of non-solvable PCEs after mitigation is higher with a look-ahead time parameter of 75 minutes. The lowest number of non-solvable PCEs after mitigation can be found with a look-ahead time parameter of 60 seconds, however, the execution time with 5 minutes is rather high but still within the limits, see Figure 25. The values have been determined using the mean of all traffic scenarios to see the trend. However, given that each traffic sample faces different environmental circumstances, the results from this analysis should also consider additional factors (e.g. time of the day, regulations etc.).

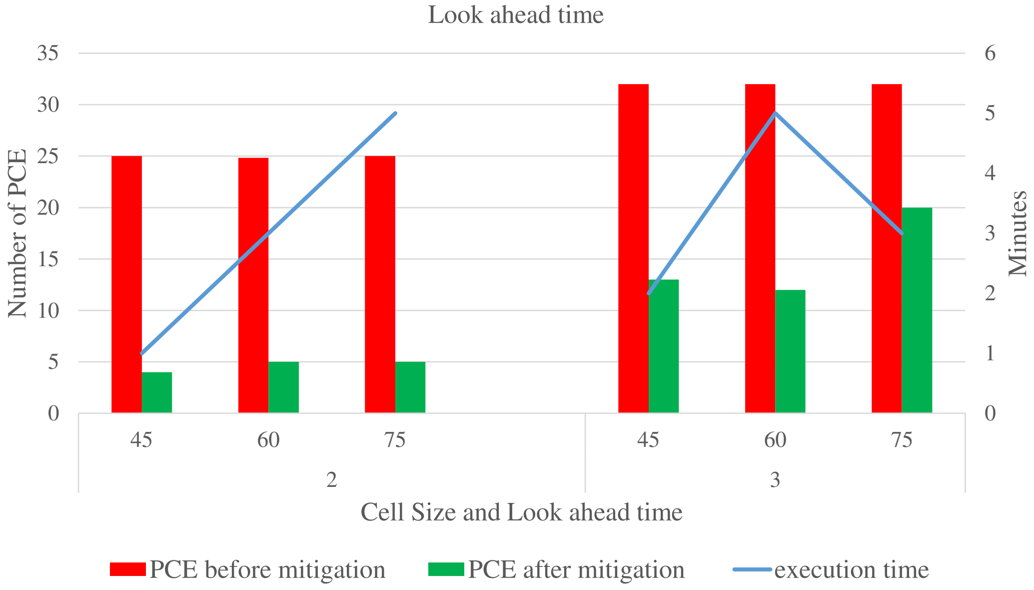


Figure 25: Summarized analysis of the look-ahead time parameter

The analysis of the cell size revealed that the number of possible CEs increases with a bigger cell size and the analysis of the cell size showed that given a bigger cell size and a greater look-ahead time parameter (L), more possible CEs remain unsolved.

4 CONCLUSION AND FUTURE RESEARCH

4.1 Conclusion

A STAM-based methodology to reduce the number of ATC interventions on air has been presented. The three-step methodology, composed by detection, analysis and mitigation, was used to develop a framework designed to be executed as a recurrent TBO service. The S-T interdependency analysis method provide a baseline to design new metrics that could support the application of alternative pre-tactical measures to the current MDI.

A sensitivity analysis resultant from the experiments has focused on determining suitable values for the cell size (S_C), the look-ahead time (L), while analysing different scenarios defined by the day of the week, time intervals and number of operating airports.

The trend of the parameters throughout different traffic scenarios has been consolidated during all experiments. However, in some traffic scenarios the number of PCEs and CEs and the percentage of solvable CEs had a significant difference. During traffic peaks (early morning hours and/or with ATC regulations), the percentage of solvable CEs was 16% whereas the possibility of solving CEs raised to 52% in traffic scenarios with lower traffic demand (late afternoon). These findings could lead to the conclusion that the acceptability of the methodology in different environments i.e. en-route, where traffic is less dense than in the LTMA could be very high. However, it is required an improvement of technological support for the trajectory prediction that could guarantee acceptable levels of uncertainty.

Significantly, the cell size parameter has showed best results when using 2NM or 3NM. However, since the cell size of 2NM could be insufficient to prevent ATC interventions during real operations, it probably will trigger an ATC intervention before the concurrence event is mitigated. Therefore, the use of a cell size parameter of 3NM shows the most appropriate value for the sample of data used if the priority of the decision-makers is to cover the most quantity of concurrence events while maintaining acceptable levels of uncertainty. The use of cell sizes of 5NM or 6NM lead to a reduced number of solved CE in exchange of a lower uncertainty values.

The experiments show that the difference between deploying the method in 2 or 4 airports has a smaller improvement on the mitigation of CEs. The effects of using different airports becomes significant when the number of departing flights (control variables) increases and when the number of interdependences between trajectories of the selected airports is reduced (e.g. to avoid redundancy in the solutions). This means that an analysis of the traffic is recommended prior selection of the airports in order to ensure a maximum number of independent control variables (PCE) is achieved. At this end, further experiments should be performed in order to understand the effects of different airports for different traffic samples.

Finally, the look-ahead time parameter has been evaluated. Considering the execution time needed to run the traffic scenarios with different look-ahead time parameters and the amount of PCEs that remain unsolved after the mitigation process, the experiments show that a look-ahead time parameter between 45 min to 60 min could be recommended. The uncertainty levels increase with the look-ahead time. However, this parameter is also associated to other factors that prevents its reduction. The ground ATC requires a minimum time to direct the flight to the stand-by/holding point, and depending on the taxi layout, once the push-back and start phase is completed, changing the sequence of take-off could not be possible. Therefore, the look-ahead time is directly linked to the airport taxi layout and the taxi times. Further analysis is required to understand the uncertainties associated to ground operations.

4.2 *Future research*

The methodology presented an ideal case that considered a high adherence nominal route for the reference trajectories. There are several sources of uncertainties that should be considered when including the human-in-the-loop. The application of the algorithm in a terminal maneuvering area support a reduction of the look-ahead time and the uncertainties associated to the take-off and ascending phases. In a terminal airspace, exist nominal routes that provides a high 4D adherence. An analysis of the nominal routes of a multi-airport system will reduce significantly the uncertainty levels associated to the TMA operations and support the selection of the airports, routes and sectors for the application of this methodology. A key aspect is the use of reference trajectories that represent the actual traffic. The analysis of historical traffic samples that determine recurrent traffic patterns will improve the selection of cell-size and look-ahead time to guarantee reduced levels of uncertainty.

In a realistic operational scenario, the ground operation inputs an important amount of latency that is expected to be absorbed by the skills of the ground ATC while issuing take-off clearances at the proposed ETOT. Consequently, further research is required to understand the impact of the presented methodology on the human performance, including the push-back, taxi operations and uncertainties associated to the typical operations of an airport (e.g. last-minute passenger delays).

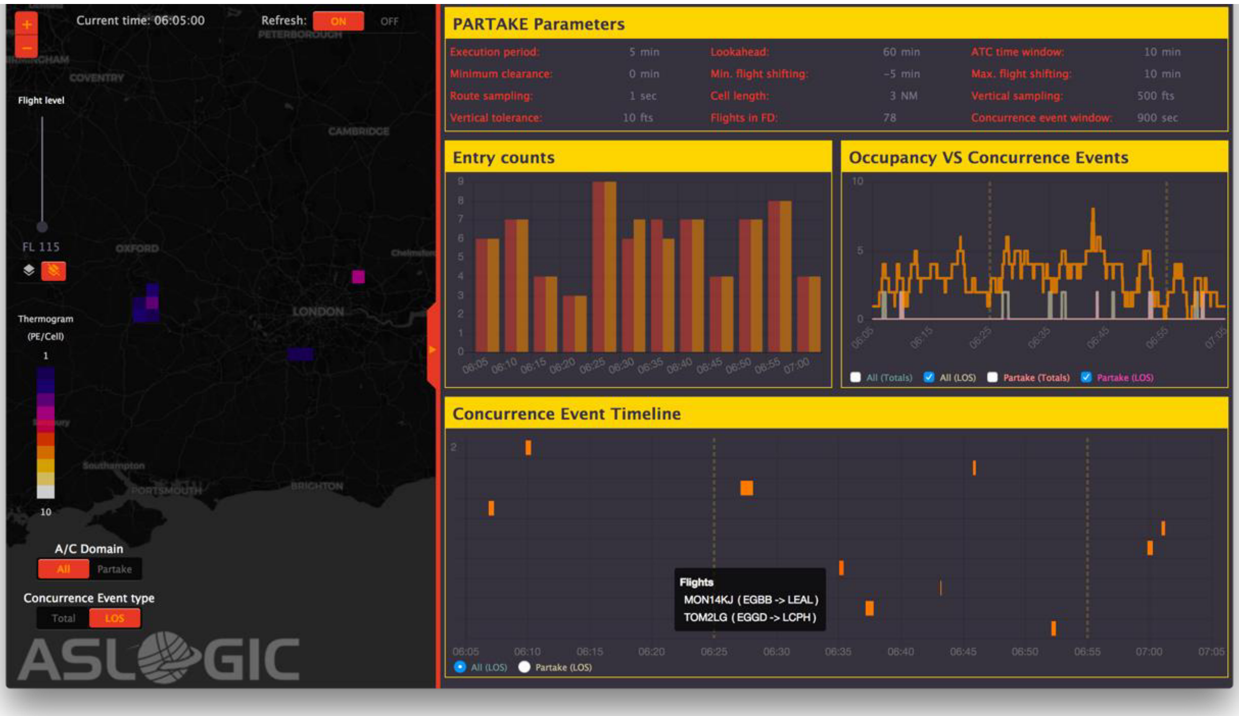
The proposed method could be used to redefine the capacity values of sectors based on quantifying the events associated to ATC interventions (e.g. a novel complexity metric targeting specific concurrence events). Further analysis is required to determine the parameters of the algorithm that actually reduces the number of ATC interventions while including the human in the loop (a very small cell-size could still trigger an ATC intervention on air).

The experiments presented in this paper uses the London terminal airspace as study case. However, it has been determined that the sensitivity of the parameters and the amount of solutions are impacted by the configuration of the scenario and the traffic sample. The application of the methodology in other multi-airport systems could help to determine the effects of the amount of traffic and the airports involved in the effectivity of the solution.

Acknowledgment

The STAM methodology presented in this paper has been designed for the European project "*cooPerative depArtuRes for a compeTitive ATM networK sErvice*" (PARTAKE) sponsored by SESAR Joint Undertaking under grant agreement No 699307 under European Union's Horizon 2020 research and innovation programme. PARTAKE (GA Ref. Ares (2016) 838948) | SESAR 2020 Exploratory Research.

The tools have been tested and verified during the development of the project and additionally, a visual interface has been designed to quick understanding of the state of the system, rising quickly and visually the situational awareness throughout the look-ahead time Figure 26.



PARTAKE Parameters

Execution period: 5 min
Minimum clearance: 0 min
Route sampling: 1 sec
Vertical tolerance: 10 fts
Lookahead: 60 min
Min. flight shifting: -5 min
Cell length: 3 NM
Flights in FD: 78
ATC time window: 10 min
Max. flight shifting: 10 min
Vertical sampling: 500 fts
Concurrence event window: 900 sec

Flights
MON14KJ (EGBB -> LEAL)
TOM2LG (EGGD -> LCPH)

Figure 26: Dashboard visualization developed in the scope of the PARTAKE project (UAB et al. 2018)

Acronyms

ANSP	Air Navigation Service Provider
ATC	Air Traffic Controller
ATFCM	Traffic Flow And Capacity Management
ATM	Air Traffic Management
CTOT	Calculated Take-Off Time
CE	Concurrence Event (loss of defined separation minima)
CEs	All Concurrence Events that have been detected with the detection tool
DCB	Demand And Capacity Balancing
DDR2	Demand Data Repository
DFS	Depth First Search
EGBB	Bristol Airport
EGGD	Birmingham Airport
EGGW	London Luton Airport
EGLL	London Heathrow Airport
EGSS	London Stansted Airport
EGTTCAP	LTMA Capital Sector
EGTTCPT	LTMA Compton Sector
EGTTTC	LTMA
EGTTVAT	LTMA Vaton Sector
ETOT	Estimated Take-Off Time
FL	Flight Levels
LTMA	London Terminal Maneuvering Area
MAS	Multi Airport System
MDI	Minimum Departure Intervals
PCEs	Concurrence Events (CE) that could be mitigated with the mitigation tool since they fulfill the requirements e.g. are still on the ground and could be delayed, belong to one of the airports that have been chosen, etc.
RBT	Reference Business Trajectory
SATM	Aerospace Transport And Manufacturing
SDS	Spatial Data Structure
SESAR	Single European Sky ATM Research
SID	Standard Instrumental Departures
STAM	Short Term ATFCM Measures
TBO	Trajectory Based Operations
TMA	Terminal Maneuvering Area

REFERENCES

CAA, 2017. *Aviation Trends - Q4*, Available at: http://www.caa.co.uk/uploadedFiles/CAA/Content/Standard_Content/Data_and_analysis/Analysis_reports/Aviation_trends/AviationTrends_2017_Q4(1).pdf.

CAPITA, 2013. *No 1778 – Service Order 16: UK TANS Charge Benchmarking - Consultancy Services for CAA's Regulatory Policy Group*,

CU et al., 2018. D6.2 - Report on Validation. , (February), p.66.

Eurocontrol, 2018a. Air traffic demand data | Eurocontrol. Available at: https://www.eurocontrol.int/service/air-traffic-demand-data [Accessed May 28, 2018].

Eurocontrol, 2017. Demand Data Repository (DDR) | Eurocontrol. Available at: http://www.eurocontrol.int/ddr [Accessed December 28, 2017].

Eurocontrol, 2007. *HOURLY ENTRY COUNT VERSUS OCCUPANCY COUNT RELATIONSHIP DEFINITIONS AND INDICATORS (1)*, Available at: https://www.eurocontrol.int/sites/default/files/library/015_Hourly_entry_vs_occupancy_count_definitions_and_indicators.pdf.

Eurocontrol, 2018b. Minimum Departure Interval - EUROCONTROL ATM Lexicon. Available at: https://ext.eurocontrol.int/lexicon/index.php/Minimum_Departure_Interval [Accessed May 28, 2018].

Lara, D., 2005. *A Benchmark and analysis of spatial data structures for physical simulations*.

NATS, 2017. United Kingdom Aeronautical Information Service. Available at: http://www.nats-uk.ead-it.com/public/index.php%3Foption=com_content&task=blogcategory&id=6&Itemid=13.html [Accessed May 28, 2018].

Netjasov, F., Janić, M. & Tošić, V., 2011. Developing a generic metric of terminal airspace traffic complexity. *Transportmetrica*, 7(5), pp.369–394. Available at: http://www.tandfonline.com/doi/abs/10.1080/18128602.2010.505590 [Accessed May 28, 2018].

Next Gen Program, 2017. Next Generation Air Transportation System (NextGen). Available at: https://www.faa.gov/nextgen/ [Accessed November 13, 2017].

Nosedal, J. et al., 2014. An efficient algorithm for smoothing airspace congestion by fine-tuning take-off times. *Transportation Research Part C: Emerging Technologies*, 44, pp.171–184.

Schefers, N., González, J.J.R. & Nosedal, J., 2016. An efficient constraint programming model for cooperative flight departures. In *18th International Conference on Harbor, Maritime and Multimodal Logistics Modelling and Simulation, HMS 2016*.

Sesar JU, 2017. SESAR Joint Undertaking | High performing aviation for Europe. Available at: https://www.sesarju.eu/ [Accessed November 13, 2017].

SESAR JU, 2016a. Agent. Available at: http://www.agent-aero.eu/ [Accessed January 31, 2018].

SESAR JU, 2016b. Partake. Available at: http://www.partake-aero.eu/ [Accessed January 31, 2018].

SKYbrary, 2017. 4D Trajectory Concept - SKYbrary Aviation Safety. Available at: https://www.skybrary.aero/index.php/4D_Trajectory_Concept [Accessed November 19, 2017].

UAB et al., 2018. D8.2 - Final Project Results Report. , (February 2018), pp.1–59.

UK Department for Transport, 2013. *UK Aviation Forecasts*, Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/223839/aviation-forecasts.pdf.