

CRANFIELD UNIVERSITY

DANY GATSINZI

A Method for ATFCM Based on Trajectory Based Operations

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING
(SATM)

PhD IN AEROSPACE ENGINEERING

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Academic Year: 2014 – 2018

Supervisors: DR. FRANCISCO JAVIER SÁEZ NIETO

DR. IRFAN MADANI

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ABSTRACT

This thesis describes a method towards a more proactive approach for Air Traffic Flow and Capacity Management (ATFCM) Demand and Capacity Balancing (DCB). This new ATFCM DCB method focuses on reducing the expected Air Traffic Control (ATC) Separation Management (SM) tactical interventions. It is based on the identification of “hotspots” and mitigating them at pre-flight phase by applying minor adjustments on aircraft’s Times of Arrivals (TOAs) at points of conflict located at en-route crossing and merging junctions (hotspots). The adjustments of TOAs are achieved through optimal speed changes in aircraft speed profiles, applied before and after each junction whilst maintaining each aircraft’s flight time and the entropy of the whole traffic network.

The approach postulates that the TOA adjustments may be transformed into a pre-tactical ATFCM DCB measure. This can be achieved by translating TOA adjustments into time constraints at junctions, issued by the Network Manager (NM) in the Reference Business Trajectories (RBTs) to produce de-randomized and well-behaved (conflict free) traffic scenarios to reduce the probability of conflicts.

Several real high-density scenarios of the current and forecasted traffic in European Civil Aviation Conference (ECAC) airspace network are simulated using specialized modelling tools to validate the method. A novel Linear Programming (LP) optimisation model is formulated and used to compute optimal speed changes that remove all conflicts in the scenarios with minimum cascading effect.

This method should enable a reduction in ATC workload, leading to improvements in airspace capacity, flight and network efficiency as well as safety. This approach is fully aligned to Trajectory Based Operation (TBO) principles. As a holistic solution, this new ATFCM DCB method should change the conventional capacity-limiting factor, currently established by the number of aircraft simultaneously entering each sector (sector count) to another factor where the level of traffic complexity, flying towards junctions is identified and mitigated at pre-flight phase.

Keywords

ATFCM, TBO, CD&R, DCB, junction, TOA, hotspot, complexity

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LIST OF ABBREVIATIONS

A/C	Aircraft
ACC	Area Control Centres
ADS	Automatic Dependent Surveillance
AFMS	Advanced Flight Management System
AIRAC	Aeronautical Information Regulation and Control
AIS	Aeronautical Information Services
ANSP	Air Navigation Service Provider
APP	Approach Control Unit
ARIMA	Auto Regressive Integrated Moving Average
ASM	Airspace Management
ATAG	Air Transport Action Group
ATC	Air Traffic Control
ATCC	Air Traffic Control Centre
ATCO	Air Traffic Controller
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATFMRP	Air Traffic Flow Management Re-routing Problem
ATM	Air Traffic Management
AU	Airspace User
BADA	Base Of Aircraft Data
BDT	Business Development Trajectory
BT	Business Trajectory
CA	Collision Avoidance

CANSO	Civil Air Navigation Services Organisation
CARD	Conflict and Risk Display
CASA	Computer Assisted Slot Allocation
CD&R	Conflict Detection and Resolution
CDM	Collaborative Decision Making
CI	Cost Index
CNS+A	Communication, Navigation, Surveillance and Avionics
CP	Constraint Programming
CPA	Closest Point of Approach
CPDLC	Controller Pilot Data Link Communication
CTA	Controlled Time of Arrival
CTO	Controlled Time Over
CTOT	Calculated Take-Off Time
CWP	Control Working Position
DAC	Dynamic Airspace Configuration
DCB	Demand Capacity Balancing
DDR2	Demand Data Repository 2
DOC	Direct Operating Costs
DP	Dynamic Programing
EC	European Commission
ECAC	European Civil Aviation Conference
ETOT	Estimated Take-Off Time
EUACA	European Union Airport Coordinators Association
FIR	Flight Information Regions

FIS	Flight Information Services
FL	Flight Level
FMS	Flight Management System
FOCS	Flight Operating Centers
FPL	Flight Plan
FR	Free Routing
FRA	Free Routing Airspace
FTS	Fast Time Simulations
GAT	General Air Traffic
GATFMP	Generalized Air Traffic Flow Management Problem
GDP	Ground Delay Problem
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMI	Human Machine Interface
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IFPL	Initial Flight Plan
IFPS	Internal Flight Plan Processing System
IFR	Instrument Flight Rule
IMC	Instrument Meteorological Conditions
LP	Linear Programming
MAGHP	Multi Airport Ground Holding Problem
MTCD	Medium Term Conflict Detection
MTF	Mid Term Forecasting

NEST	Network Strategic Tool
NM	Network Manager
NMOC	Network Manager Operations Centre
NOP	Network Operations Plan
NSA	National Supervisory Authorities
OAT	Operational Air Traffic
PANS	Procedures for Navigation Services-Air Traffic Management
PARTAKE	DepArtuRes For A CompeTitive ATM NetworK Service
PBN	Performance Based Navigation
PCP	Pilot Common Project
PMM	Point Mass Models
PODM	Passenger Origin-Destination Model
PRR	Performance Review Report
PSR	Primary Surveillance Radar
PZ	Protected Zone
RBT	Reference Business Trajectory
RNAV	Area Navigation
RNP	Required Navigation Performance
RO	Research Objectives
RVSM	Reduced Vertical Separation Minima
S&A	See and Avoid
SAGHP	Single Airport Ground Delay Problem
SAL	Slot Allocation List
SBT	Shared Business Trajectory

SCR	Semi Circular Rule
SES	Single European Sky
SESAR	Single European Sky ATM Research
SM	Separation Management
SSR	Secondary Surveillance Radar
STAM	Short-Term ATFCM Measure
STATFOR	Statistics and Forecasts
STCA	Short Term Conflict Alert
SWIM	System Wide Information Management
TBO	Trajectory Based Operations
TCAS	Traffic Collision Avoidance System
TM	Trajectory Management
TMA	Terminal Manoeuvring Area
TOA	Times of Arrival
TP	Trend Prediction
TRACT	Traffic Adjustment Through Constraint of Time
TS	Traffic Synchronisation
TSE	Total System Error
TTA	Time of Arrival
TTO	Time to Overfly
TWR	Aerodrome Control Tower
UDPP	User Driven Prioritisation Process
US	United States
VDL	VHF Digital Link

VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
WAM	Wide Area Multilateration

1 INTRODUCTION

1.1 The Air Traffic Management System Context in Aviation Industry

The aviation industry can be defined as a combination of all facets involved in both aircraft (A/C) manufacturing and its use for transportation. Recent studies have described the aviation industry as a socio-technical network system, which has evolved since the invention of first aircraft in 1903 into the current global air transport system, where aircraft are one of its several facets [1] [2]. The commercial aviation industry, in particular, is today a significant component of global economy. It is estimated that 40% of world trade by value is carried by air transport and 4.5% of world economic output is associated with the civil aviation component of air transport [3]. According to the findings by Air Transport Action Group (ATAG) [4], the aviation industry as a whole generates 29 million jobs globally through direct employment and through employment in its associated indirect economies. The stated impact of air transportation varies over time, and the above findings may vary by study, but the importance of commercial aviation industry worldwide is beyond doubt [5].

It is commonly acknowledged that when any invention evolves into a large socio-technological network, it starts to develop at a rate driven by both the historical events that shape it, and innovations developed to meet its expected short-term and long-term challenges [6][7]. In this context, when air transport started to develop and grow, the need for an organised system to manage the air traffic both on the ground and in the air was evident, and eventually this need led to the introduction of Air Traffic Management (ATM) system as an essential component of aviation industry [8]. When two or more aircraft occupy the same airspace or airport, they are referred to as the “air traffic”, which needs to be managed at all times to ensure the safety and efficiency of flights. The ATM system is an essential enabler of air transport, which manages air traffic. This thesis is focused on this component of aviation industry, “the ATM system”.

The international Civil Aviation Organisation (ICAO) defines the ATM as the dynamic and integrated management of air traffic and airspace in an efficient, economical and safe manner, through the provision of facilities and seamless services in collaboration

with all air transport stakeholders [9]. Therefore, when the ATM system is referred to, it includes the ground and airborne functions consisting of systems, people and procedures that together enable safe, efficient and economic operations of air transport.

The current ATM system integrates three main components: The Airspace Management (ASM), Air Traffic Flow and Capacity Management (ATFCM) and Air Traffic Services (ATS) [10][11]. These components conceptually operate at different planning layers, defined based on the available time to react from the moment when flight operation starts as illustrated in **Figure 1**.

1. ***Airspace Management (ASM)***: Performs all functions related to the planning of airspace infrastructure and its organization such as sector configuration, design of air routes and procedures. The ASM functions are typically performed within days up to years before the moment of flight operation.
2. ***Air Traffic Flow and Capacity Management (ATFCM)***: Performs Demand and Capacity Balancing (DCB) functions, in order to balance the capacity of airspace and airports according to the established baseline of air traffic demand. The current ATFCM system controls hourly demand of airspace sectors and updates flow regulations by imposing aircraft ground delays and aircraft re-routes. The ATFCM functions are typically performed within one hour to months before the time of flight operation.
3. ***Air Traffic Services (ATS)***: Contains Air Traffic Control (ATC) system, Flight Information Services (FIS), alerting services and other advisory services. The ATC in particular, performs all tasks required for tactical control of aircraft. These tasks mainly include real time surveillance of aircraft, communication with aircraft and Conflict Detection and Resolution (CD&R) of aircraft conflicts.

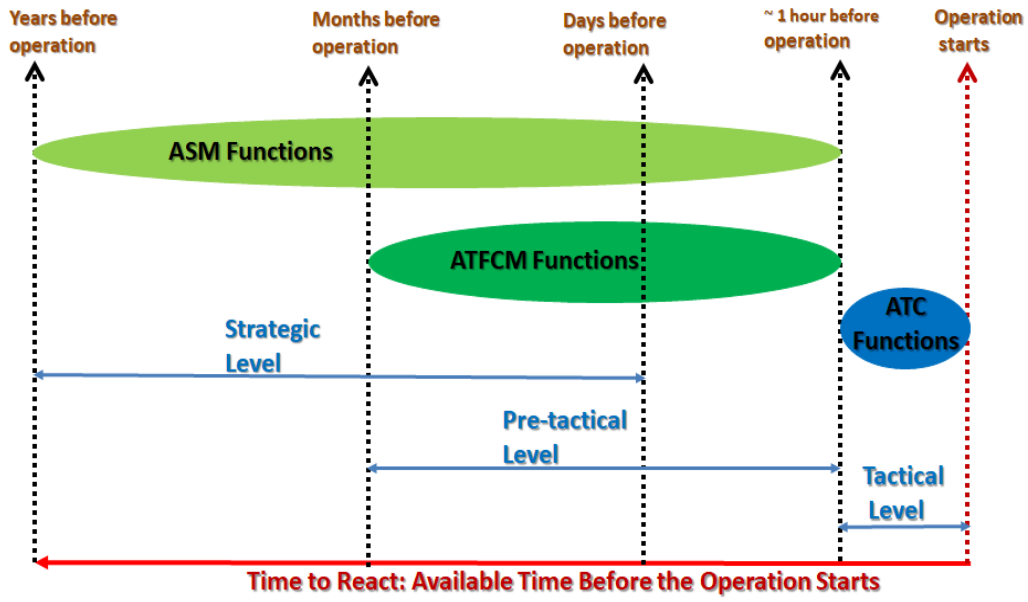


Figure 1: ATM planning layers

1.2 The Research Motivation

1.2.1 The ATM Heritage and Its Current Bottlenecks

Since its inception, the ATM system has undergone several significant changes, evolving from a primitive form based on simple operational rules, to a complex network supported by sensors, communication and control subsystems [12]. The evolution of these technical enablers such as radio communication, navigational aids (NAVAIDS) and radar systems that revolutionized the way ATM system was operating in 1950s still forms the backbone of current ATM system [12]. Derived from these ancient supporting technologies, the current ATM system is still essentially based on a network of fixed routes and ATC sectors.

To achieve the required levels of safety for air traffic across this network, a human supervisory control system is applied. The supervision process is currently mainly based on Air Traffic Controllers (ATCOs) who detect and solve aircraft conflicts within each ATC sector in a reactive manner. The ATC sectors are volumes of airspace defined to enable the distribution of ATCOs' workload. This conventional airspace organization is demarcated by the ASM and it constitutes a network of fixed routes, sectors and nodes. This organization enables the ATCOs to have a priori information on the location of

aircraft conflicts since these conflicts are typically located at the crossing and merging points of ATS route network.

When the current ATM with its conventional ATS route network and ATC sectors was designed in 1950s, the current traffic density could not have been anticipated [13][14]. Indeed, it is estimated that from 1989 to 2015, the air traffic flows in Europe have increased by 33% [13]. **Figure 2** shows the air traffic flows in Europe in 1989 (left image) when compared to air traffic flows in Europe in 2015 (right image).

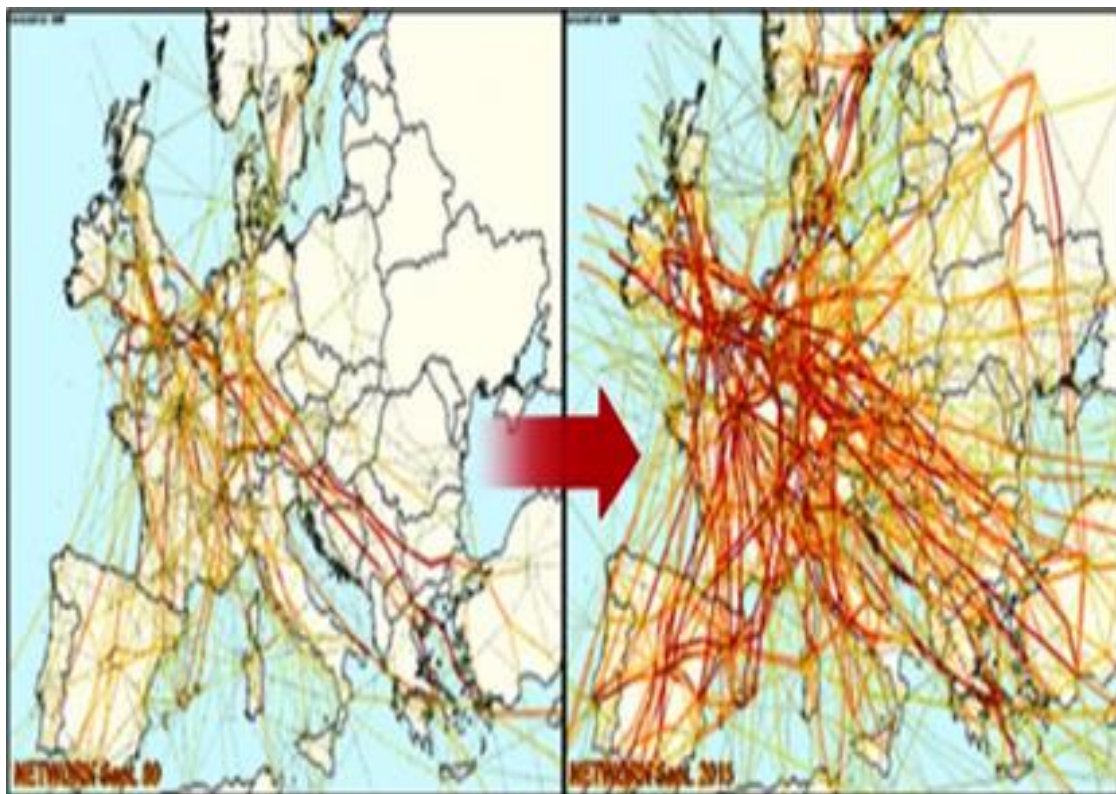


Figure 2: The air traffic flows in Europe in 1989 (left Image) and in 2015 (right Image) [13]

The global cumulative air traffic growth has been very significant over the past few decades. This growth has currently determined a certain degree of saturation in certain airports and parts of airspace, resulting in the exacerbation of delays that causes extraneous costs [15]. Due to these new challenges, together with forecasted sustained traffic growth trends, the ATFCM being the ATM component concerned with managing the balance between air traffic demand and the airspace capacity which is limited by the

ATC operational resources, have been the object of several research programs [16][17][18]. These programs seek to forge new ATFCM initiatives that are suitable to face these new ATM challenges. This thesis also contributes towards this effort.

Conventionally, in order to prevent ATCO workload overload and improve flight efficiency and safety, the ATFCM regulates traffic flow into sectors. However, airspace resources are currently used to attend traffic demand whilst suffering from saturations that foster ATFCM regulations such as aircraft ground delays and re-routings. This is more significant at high traffic density airports and ATC sectors in Europe. According to the EUROCONTROL Performance Review Report (PRR) [15], considering only the ATFCM en-route delays in 2016; an average of 51 seconds delay per flight and a total of 8.7 million minutes delay were recorded in the European Civil Aviation Conference (ECAC) area, resulting in en-route ATFCM delay costs estimated at €8.7 million. In addition, forecasts indicate that there is an expected increase in air traffic demand with the potential to increase further the air traffic congestion and delays, hence, reducing ATM operational efficiency.

EUROCONTROL Statistics and Forecasts (STATFOR) have performed a mid-term forecast of Instrument Flight Rule (IFR) movements in the Reference Area (ESRA08) region, covering a period from 2012 to 2035 [19]. This forecast was generated considering four different growth scenarios “A, C, C’ and D”, where each scenario represents different economic, technological, and environmental parameters as defined in **Table 1**. This forecast indicate that, for the most likely scenario (Scenario C – Regulated Growth), there will be 14.4 million IFR movements in ESRA08 in 2035 which represents 1.5 times more traffic than in 2012 as shown in **Figure 3**. In addition, based on the results obtained in all the four scenarios, average annual growth rates ranging between 0.7% and 2.6% and extra 5000 to 21000 IFR flights each day are expected in 2035 compared to 2012 as summarised in **Table 1**.

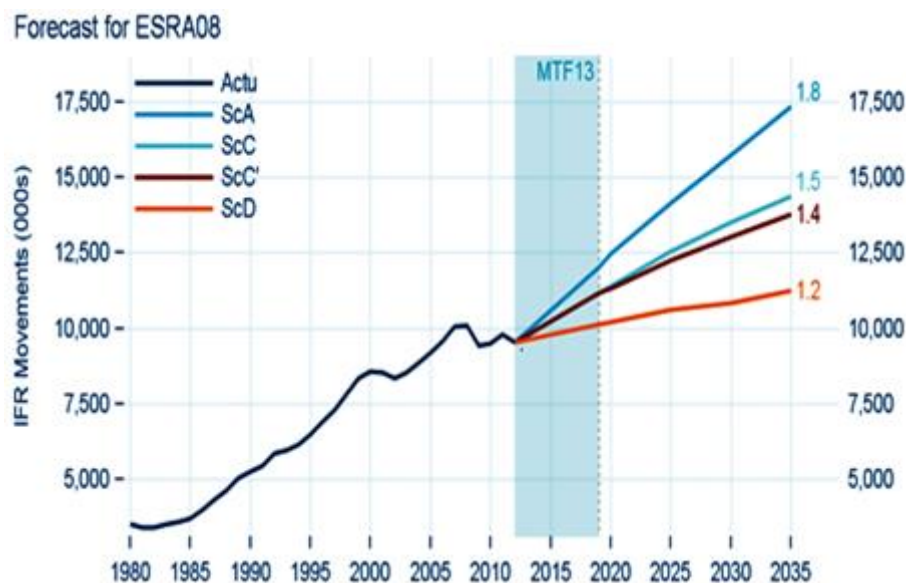


Figure 3: EUROCONTROL STATFOR IFR movement predictions in ESRA08 for the year 2035 [19]

Scenario	IFR Mvts (million) 2035	Traffic Multiple 2035/2012	Ave Annual Growth 2035/2012	Extra flights/day (thousands)
A: Global growth¹	17.3	1.8	2.6%	21
C: Regulated Growth²	14.4	1.5	1.8%	13
C': Happy Localism³	13.8	1.4	1.6%	12
D: Fragmenting World⁴	11.2	1.2	0.7%	5

Table 1: STATFOR forecast traffic growth trends [19]

¹ Strong economic growth, increasing globalisation, resource availability enhanced by technology

² Moderate economic growth, regulations to take into account the stakes of sustainable development (Most-likely)

³ Moderate economic growth but with European economies being more and more fragile, increasing pressure on costs, stricter environmental constraints

⁴ Increasing tensions between regions, leading to reduced trade and weaker economies

The above forecasted growth trends are more than what the current European ATFCM can digest. In fact, according to [20], in the most likely scenario, the forecast results suggest that about 1.9 million flights which accounts for 12% of total demand will not be accommodated by the current ATM capacity in 2035.

Figure 4 shows the comparison of distribution of daily projected delay by time length in ESRA08 region due to increased congestion from 2012 to 2035 according to EUROCONTROL forecast [19]. In **Figure 4** for instance, it is shown that about 2000 flights each day will be delayed by 30 minutes in 2035 as compared to 400 flights that were delayed for the same time length in 2012.

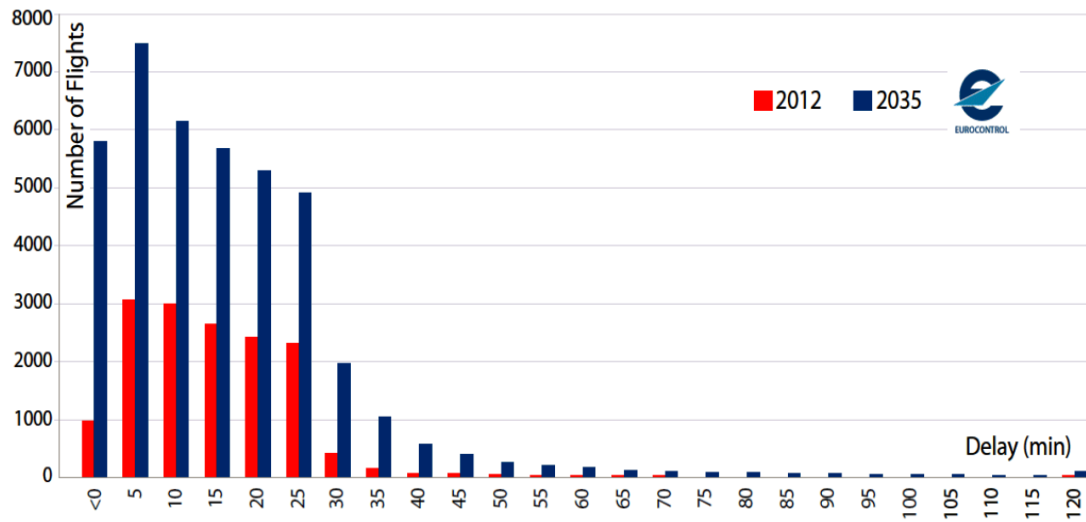


Figure 4: Current and projected daily delay distribution due to increased congestion in ESRA08 region [19]

In addition, other challenges such as the ever-increasing expectation on safety and aviation environmental impact, rising fuel prices and a tough financial climate driving the need to reduce the air transport operating costs are significant. Therefore, the current traffic situation and the forecasted air traffic growth drive the need to improve the ATCFM system in order to deal with the emerging traffic demand and capacity balancing challenges.

1.2.2 The Impact of Conventional ATFCM DCB on ATC Workload and Airspace Capacity

The current aircraft operation is structured into ATM pre-flight planning and execution layers. These layers have their specific roles and objectives achieved according to the available time to react⁵. Pre-flight planning layers act at strategic and pre-tactical levels where they focus on the objective of providing flight efficiency whilst tactical layers focus on safety issues. **Figure 5** illustrates the relevancy of these two ATM objectives (safety and flight efficiency, represented by sky-blue and amber zones respectively at the top of right-hand side graph) vs. the available time to react.

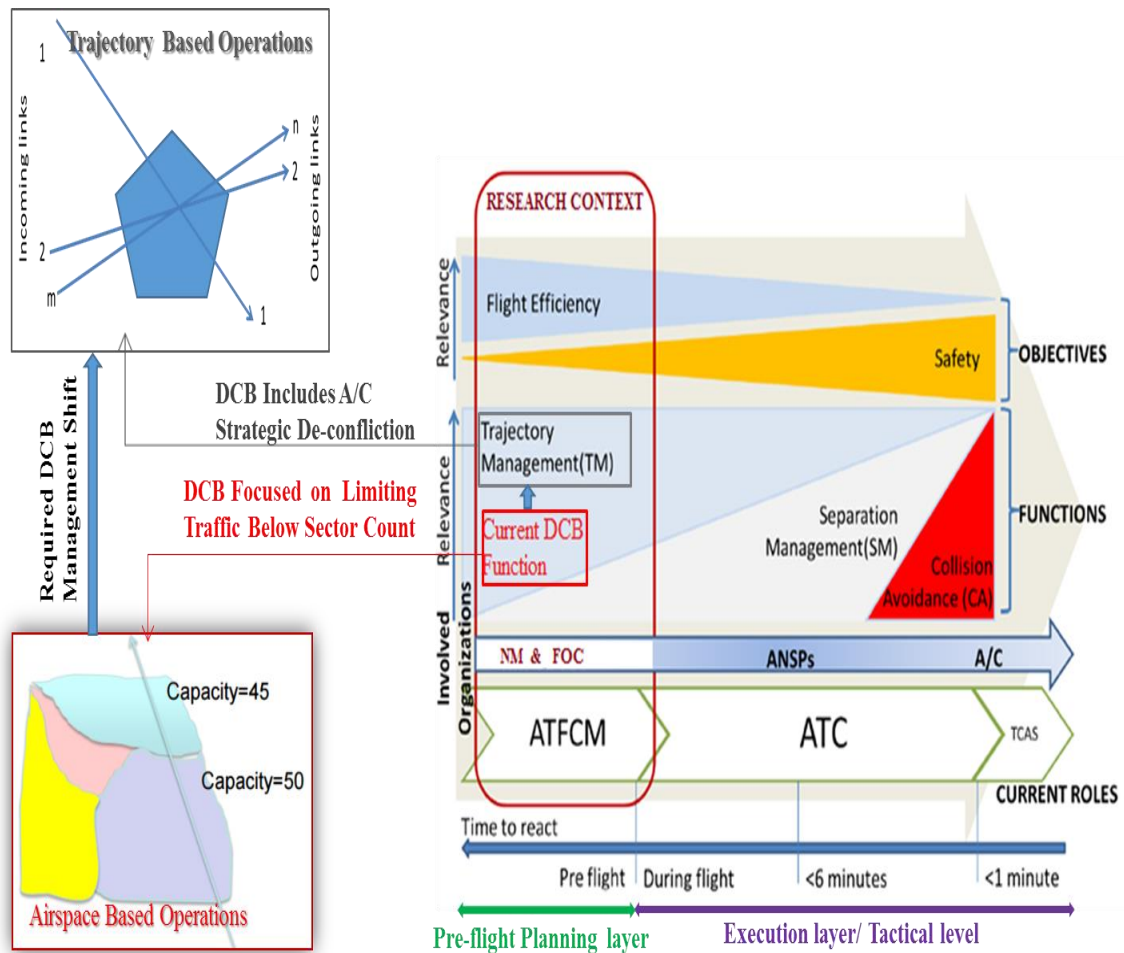


Figure 5: The current ATM planning layers and role of involved systems

⁵ Available time before the conflict occurs

Figure 5 depicts that these objectives are achieved by different ATM systems and agents/organisations through different management activities/functions. It also depicts that the relevancies of these objectives counter-act each other towards the time to react, where safety becomes more of a focus with decreased time to react whilst flight efficiency becomes less of a focus and vice versa with increased time to react.

As also shown in **Figure 5**, currently, at tactical level where the time to react is from when the aircraft is already in the air (during flight) down to <1 minute before conflict, activities involve ATC and aircraft (i.e. on-board TCAS). The actions on resolving safety issues through Separation Management (SM) and Collision Avoidance (CA) functions are performed in a reactive manner. On the other hand, at pre-flight layer, the ATFCM focuses on providing flight efficiency in the air traffic network. This is achieved through the DCB function. The DCB function is applied considering the region of interest which is normally a wide region such as ECAC area in Europe, where the main involved agents are the Network Manager (NM), airports, air traffic control centres (ACC) and airlines' Flight Operation Centres (FOCs). The DCB function is currently achieved using different measures, which mainly relies on limiting the maximum acceptable expected hourly aircraft entry count into sectors, or sometimes the sector occupancy count [21]. Anytime this limit is reached, the involved aircraft are then regulated in order to maintain an acceptable ATCOs' workload.

Currently, there is no clear pre-tactical consideration of conflicts at pre-flight layer, since the maximum allowable number of aircraft entering (sector count) or within a sector (occupancy count) for a given period is fixed regardless of particular expected air traffic complexity that may result from the conflicts that are inherent in aircraft flight plans. This makes the current ATM system to rely solely on ATCOs' skills to tactically detect and resolve these conflicts, which impacts their workload.

With the increase of traffic in ATC sectors, the ATCOs' workload also increases. This limits the number of operations that can be attended safely and efficiently by each ATCO in each ATC sector [22]. Therefore, the current airspace capacity strongly depends on the individual capacity of each ATC sector. The workload experienced by ATCOs, estimated by the expected aircraft hourly entry count in each sector, is then the

main limiting factor of the whole airspace capacity; thus, the current ATM operations are referred to as “airspace based operations”.

The current ATFCM DCB methods are anchored to the “airspace based operations concept” rather than the new “Trajectory Based Operations (TBO) concept” and it is broadly recognised that they are no longer efficient to deal with sustained increasing traffic levels [2][23][14]. Therefore, a shift is required in the current ATFCM to focus the DCB function on Trajectory Management (TM) as proposed in TBO concept (see Section 1.3). This shift is expected to enable the identification and mitigation of conflicts at pre-flight layer in order to reduce the ATC workload as proposed in this thesis (see Sections 1.4 and 1.5). This DCB management shift from “airspace based operations” to “TBO” is illustrated in **Figure 5**.

1.3 Forging the Way-Forward

To overcome the discussed ATM limitations, new initiatives such as those proposed by the Single European Sky ATM Research (SESAR) in Europe [24] and its United States (US) counterpart the Next Generation Air Transport System (NextGen) [16], seek to reform the paradigm for the ATM system. A key common pillar of these new initiatives is the aforementioned transition from the conventional airspace based operations to TBO. The TBO relies on the 4D trajectory⁶ concept, where aircraft are expected to fly close to Airspace Users’ (AUs’) preferred trajectories whilst meeting the performance requirements defined in the associated flight procedure. Under this TBO principle, all ATM stakeholders will collaboratively achieve these trajectories. Constraints associated to ATFCM will be solved under the principle of obtaining trajectories that suits AUs’ internal business objectives.

The aforementioned performance requirements as defined in ICAO’s Performance Based Navigation (PBN) concept [25], will allow aircraft to navigate their flights accurately, following a planned centered-line trajectory either under “Free Routing” (FR) airspace or following the conventional route structure [26],[27]. This flexibility, however, brings new challenges; the application of FR concept changes the current

⁶ The 4D trajectory of an aircraft consists of the three spatial dimensions plus time as a fourth dimension

fixed and well-defined “crossing points” in the ATS route network where most of conflicts are conventionally expected to occur, hence, removes the earlier mentioned current ATCOs’ priori information on the location of aircraft conflicts.

In FR Airspace (FRA), the number of trajectories’ crossing and merging points can be expected to increase which could make the complexity of airspace to increase, although, for the same population of these points, the number of aircraft crossing them could averagely reduce [28]. However, since the conflicts are broadly distributed in FRA, the ATCOs’ workload in terms of detecting them should increase [28].

The TBO concept enables new ATFCM DCB methods such as that proposed in this thesis, where the expected conflicts between aircraft trajectories can be identified and mitigated at pre-flight layer. As summarised in **Figure 6**, it is expected that identifying conflicts and mitigating them at strategic/pre-tactical levels, could bring a reduction in ATCOs tactical interventions, hence increasing the airspace capacity.

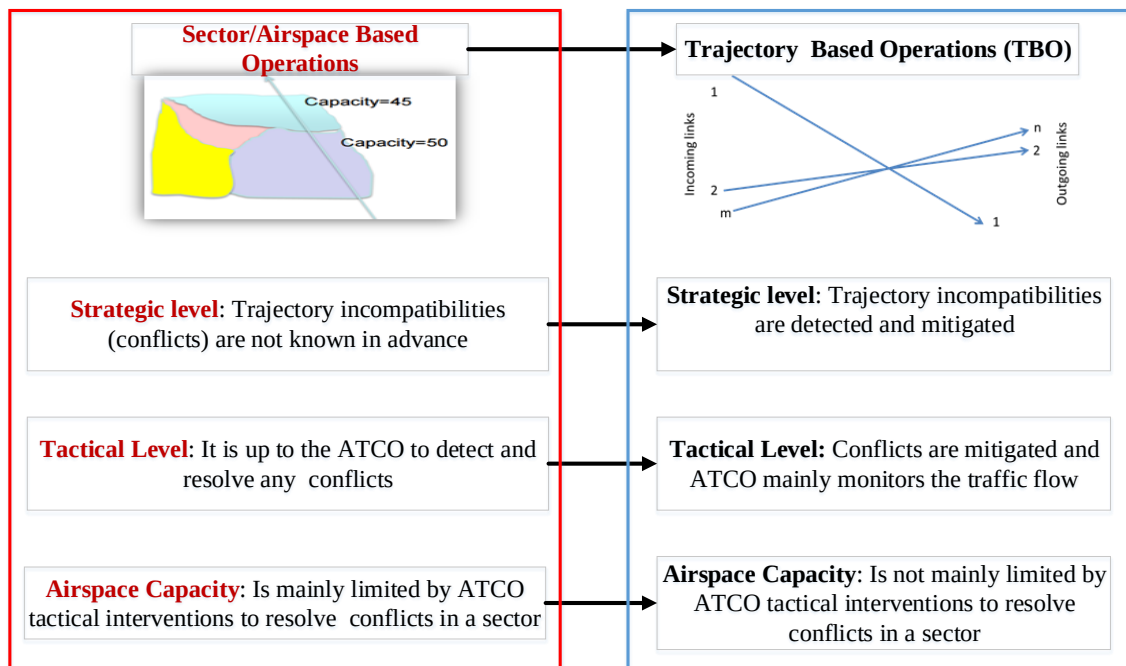


Figure 6: Potential benefits of TBO based pre-flight aircraft de-confliction

To achieve the TBO benefits outlined in **Figure 6**, according to ICAO Doc.9854 “Global Air Traffic Management Operational Concept” [9], the ATFCM DCB function shall operate at strategic, pre-tactical and tactical levels, at which all stakeholders of

ATM will be involved in order to increase operational efficiency. The last of these ATFCM DCB stages, the tactical DCB stage, shall focus on the following specific objectives:

1. Through collaborative decision-making (CDM), perform dynamic adjustments to the organisation of airspace in order to balance capacity;
2. Perform dynamic changes to the entry/exit times for aerodromes and airspace volumes and adjustments to the users' schedules.

Several European ATM projects have recently focused on developing initiatives to provide de-confliction functions for aircraft 4D trajectories, exploring the impact of applying trajectory time constraints at given waypoints in an effort to achieve the second objective above [29][30][31]. A key pillar required for the implementation of these new ATFCM DCB initiatives, is to consider the 4D trajectory as the basis for traffic management at both the planning and execution phases of ATM system. These 4D trajectories must be continuously managed during their whole life cycle.

The 4D trajectory concept describes for each flight, its intended trajectory defined with a required accuracy associated to all three spatial coordinates (3D) and target time or time constraints at designated waypoints [32]. The 4D trajectory management evolves out of a collaborative-layered planning life cycle that spans through different phases. The Reference Business Trajectory (RBT), which is the trajectory AU agree to fly and airports and Air Navigation Service Providers (ANSPs) agree to facilitate, is an outcome of associated DCB process [11][33]. The RBT is a reference, but it is not required to adhere with specific margins in time or space, unless some initial constraints are added to its specification. The RBT update and revision processes are an integral part of SESAR target ATM concept [34].

The existing trajectory de-confliction initiatives in the literature have been only applied at tactical in-flight/execution layer with short time to react horizons. This is mainly due to the ATM system's uncertainties that increase with available time to react. However, as the 4D trajectory will be negotiated and agreed before the flight under TBO, and AUs will commit to fly the aircraft with the required accuracy and precision along the agreed

trajectory, the resulting increased accuracy of flight planning and flight execution, will enable the implementation of pre-flight aircraft de-confliction to support ATFCM DCB process.

1.4 The Problem Statement, Research Aim and Objectives

1.4.1 The Problem Statement

In the existing research initiatives, pre-flight de-confliction at hotspots (conflicted en-route junctions) achieved through RBT revision at pre-flight phase for ATFCM DCB purposes, has not yet been considered. The current ATFCM methods applied to balance between demand and the system's resources (capacity) to avoid the overload of ATC workload rely on criteria of limiting the maximum number of hourly aircraft entry count and or aircraft occupancy count of expected traffic into the ATC sectors below a maximum threshold. Anytime this maximum threshold is reached, the involved aircraft are regulated by the ATFCM to maintain an acceptable ATC workload. This maximum threshold is however fixed, regardless of particular expected air traffic complexity resulting from aircraft trajectories' spatiotemporal interdependencies (conflicts) that are inherent within aircraft flight plans, which may greatly affect the ATCOs' workload.

The ATFCM DCB measures that are based on the above criteria are still anchored in the conventional ATM operations, rooted in the concept of "airspace based operations". It is broadly recognised that these measures are no longer efficient to deal with the sustained increasing traffic density [11][34][35]. It is then necessary to reformulate the current ATFCM DCB process to align with the new TBO concept. Under TBO, the ATFCM DCB process is expected to involve pre-flight de-confliction measures that enable reduction of conflicts at tactical level, thus, reducing the ATC workload by minimising ATCOs Separation Management (SM) tactical interventions. For en-route operations, this expectation is articulated in SESAR Master Plan [11], which states that, "*the goal of SESAR concept is to deploy tools to manage complex situations in order to reduce ATC workload by strategic de-confliction measures within the new ATM system*". Therefore, there is an existing gap between this SESAR expectation and the existing ATFCM research initiatives. It has not been yet described in the literature how de-

confliction at pre-flight layer (strategic level and pre-tactical level) will be achieved nor elaborated how it can affect the ATC workload and improve the airspace capacity. This research bridges this gap by answering the following key research question:

How can aircraft de-confliction at pre-flight phase be achieved in a TBO environment, and how could it affect the ATC workload and airspace capacity?

Attempting answering the above key research question raises other more specific questions, the following open questions are addressed and/or discussed:

1. What are the limitations of current ATFCM measures and what are the possible ATFCM improvements to reduce them?
2. Is pre-flight de-confliction of aircraft trajectories possible in TBO environment?
3. How can pre-flight trajectory de-confliction be used as an ATFCM DCB criterion for demand measure in a TBO environment?
4. What levels of trajectory uncertainties should be considered for pre-flight trajectory de-confliction?
5. What should be the criterion for aircraft trajectories' compatibility at junctions that reduces ATCO SM tactical interventions?
6. Can minor changes in aircraft speed profiles be applied to achieve pre-flight de-confliction to reduce ATC tactical interventions and can they be operationally acceptable?

1.4.2 Research Aim and Objectives

The work carried out in this research aims to propose an ATFCM method that is aligned with TBO, in order to change the current airspace capacity-limiting factor and reduce ATCOs' SM tactical interventions at pre-flight phase. To achieve this aim, the following specific research objectives (RO) are defined:

1. Study and analyse the effect of new ATM paradigm shift from the current airspace based operations to TBO on the performance of ATFCM DCB function.

2. Propose and describe a novel ATFCM DCB method based on hotspot identification and mitigation at pre-flight phase (RO#2).
3. Analyse and estimate the main uncertainties affecting the aircraft's Time of Arrival (TOA) at a junction (RO#3).
4. Establish a new criterion for aircraft trajectories' compatibility at junctions that reduces ATCO SM tactical interventions in the presence of above trajectory uncertainties (RO#4).
5. Formulate a new optimisation mathematical model to implement the proposed ATFCM method (RO#5).
6. Verify the model by simulation and analysis of its performance, addressing different traffic flow scenarios (RO#5).
7. Outline further works to cover the limitations noted on completion of research (RO#7).

1.5 Thesis Main Contributions

There are a number of novel contributions described in this thesis:

This thesis bridges the aforementioned gap between SESAR expectation and existing research approaches, by proposing a different approach for identifying, as far in advance as possible, during the pre-flight DCB timeframe, the expected traffic demand that produce aircraft spatiotemporal interdependencies at hotspots (en-route conflicted junctions), which are likely to require ATCOs' tactical interventions. In order to identify the overall trajectory interdependencies, the proposed method assesses the links among all the identified conflicts including their upstream and downstream impact on the ATM network, and computes the optimal solution for their integrated statistical reduction. This is achieved by including time constraints' specifications into the RBTs to remove proactively at pre-flight phase, the conflicts at the crossing and merging points (junctions) by incorporating minor adjustments in aircraft's TOAs at these junctions.

The new ATFCM method proposed in this thesis introduces a study on reducing ATCOs' SM tactical/reactive interventions based on a novel concept of "hotspot

identification and mitigation at per-flight ATFCM DCB timeframe”. In the mitigation process, the method produces optimal speed changes as the control variables computed before the flight to provide the required TOA adjustments at junctions, in order to have a de-randomized and well-behaved (conflict free) traffic whilst maintaining each aircraft’s flight time and the entropy of the whole traffic network.

The new TOAs at junctions for all aircraft that remove the conflicts, applied to help in solving the DCB problem at pre-flight phase, are computed using a novel Linear Programming (LP) optimisation model. This LP model minimises the scalability problem inherent in the existing ATFCM optimisation methods, especially when applied to high-density traffic environments such as the ECAC airspace.

The method presented in this thesis also seeks to change the current capacity-limiting factor, established by the number of aircraft entering or occupying simultaneously each sector, to other criteria where the level of traffic complexity is identified and mitigated.

The ultimate goal of this thesis in the operational ATM context, as it is in the conventional DCB procedures, is to maintain the number and complexity of expected required ATC SM tactical interventions at reasonable levels, from the ATCOs’ workload perspective.

This thesis formulates how to deal with flight plans in the future ATM, assuming that ATFCM will issue RBTs containing Targeted Time of arrival/ Time to Over-fly (TTA/TTO)⁷ constraints, reducing significantly the ATC SM tactical interventions. The regional Network Manager (NM) shall issue these constraints at pre-flight phase to improve the regional traffic network performance.

⁷TTA is a progressively refined planning time that is used to coordinate between arrival and departure management, while, TTO is a time stamp over relevant en-route waypoints. Both TTA/TTO are new SESAR target times considered able to support DCB, in such a way that TTA/TTO constraints can be used as 4D Trajectory constraints needed to optimally adapt airspace capacity to the demand and minimise demand adjustments.

1.6 Publications Arising from this Work

1. D. Gatsinzi, F.J.S. Nieto, and I. Madani, “Development of a new method for ATFCM based on trajectory based operations,” *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*. 2017; 0(0).
2. D. Gatsinzi, F.J.S. Nieto, and I. Madani, “Hotspot Identification and Mitigation at Strategic Level by Subliminal Changes in Aircraft Time of Arrival at Junction,” *Proceedings of the SESAR Innovation Days (2016): Inspiring long-term research in the field of air traffic management*, 8 - 11 November 2016, Delft, The Netherlands, paper number: 15.
3. D. Gatsinzi, F.J.S. Nieto, and I. Madani, “ECAC Use Case of Optimised Pre-tactical Time of Arrival Adjustments to Reduce Probability of Separation Infringements” *The 15th IFAC Symposium on Control in Transportation Systems (CTS 2018)*, June 6-8, 2018, Savona, Italy.

1.7 Organisation of the Thesis

Chapter 1 provides the background of the thesis including the fundamentals of air transport and ATM System, with a special focus on the ATFCM DCB function. It establishes the background of the research problem to identify the existing deficiencies in ATFCM DCB approaches, which leads to the articulation of research questions, aim and objectives as well as a summary of main research contributions to knowledge. A number of publications arising from this research are then outlined, followed by an outline of thesis organisation.

Chapter 2 provides a comprehensive review of ATM system including its sub-systems, stakeholders and technological enablers. Particular attention is paid to the scope of ATFCM DCB problem in the context of both the conventional ATM operations and new ATM modernisation concepts.

Chapter 3 provides a critical review of most comprehensive approaches for ATFCM DCB optimisation problem from both the state-of-the-art in literature and from the

regulatory initiatives. This review leads to the identification of research gaps; ensuring novel contributions from the research are properly defined. This chapter also formulates the problem statements presented in Chapter 1. It then provides taxonomy of specialised data sources and software tools used to support the methodology followed in this thesis. This taxonomy enables the familiarization of discussion in the subsequent chapters.

Chapter 4 starts with a description of operational environment in which the proposed ATFCM DCB method is applied and analysed. This operational environment is described in terms of research context in ATM planning layers within the TBO environment and the considered airspace network and environment. From this described operational environment, a set of main operational conditions and aircraft and systems capabilities are assumed to limit the scope and to substantiate the methods applied in this thesis. A framework of methodology followed along with the specific methods applied is provided in this chapter.

Chapter 5 concerns the conceptual characterisation and mathematical modelling of problem. First, the considered airspace network topology and the topology of junctions are characterised using a complementary Lagrangian-Eulerian modelling approach. The proposed ATFCM DCB method, which is based on the identification of conflicted en-route junctions (hotspots) and mitigating them at pre-flight phase, is then defined and the solution scope is established. This is followed by the description of proposed method to mitigate hotspots, which is based on minor adjustments of aircraft TOAs at junctions, achieved through optimal changes in aircraft speed profile. This chapter also establishes the trajectory compatibility condition, which is based on the derived uncertainties in the aircraft TOAs at junction and the desired probability of aircraft simultaneous arrival at junction. A novel LP optimisation model that computes the optimal speed changes required of each aircraft to remove the hotspots is formulated by considering all potential spatiotemporal interdependencies of all aircraft planned trajectories as well as their upstream and downstream impact on the ATM network.

Chapter 6 discusses the preliminary simulations and analysis of results to verify quantitatively the performance of models developed in Chapter 5. Several scenarios considering different scopes of problem are discussed where the corresponding

simulation results are then analysed. The first scenario verifies the conflict removal of a single pairwise crossing junction without consideration of TOA uncertainties. The second scenario expands the scope in the first scenario by considering removal of crossing and merging conflicts at single and multiple conflicted junctions along aircraft trajectories for all aircraft in the network, considering TOA uncertainties. Several other scenarios are simulated to analyse the characteristic behaviour and performance of proposed LP model in different levels of traffic densities and operational situations. The last section of this chapter presents a basic analysis on the effects of proposed ATFCM DCB method on the flight operating costs.

Chapter 7 discusses scenarios of real high-density traffic in the ECAC airspace that is used in simulations to validate the proposed method as a viable ATFCM DCB solution. Several simulations are presented considering different conflict scenarios in a current high-density ECAC traffic network. A discussion on the feasibility of TOA adjustments in both AU and ATC perspectives is provided in this chapter. A forecasted high-density traffic scenario in ECAC area for 2022 is also described and simulated for validation of proposed method. Finally, a complementary qualitative analysis based on a Subject Matter Experts (SMEs) opinion collected from a small-scale structured questionnaire to probe the AUs acceptability is provided.

Chapter 8 concludes the thesis by summarising its main achievements and the main potential ATM operational impact of the proposed method. It also outlines the thesis limitations and identifies opportunities for further work.

2 THE SCOPE OF ATFCM PROBLEM IN THE CONTEXT OF CONVENTIONAL AND NEW ATM CONCEPTS

2.1 The ATM as a Human System Integration Problem

It is widely acknowledged that air transport is the fastest and one of the safest methods of transport [5]. To make this possible, the complex processes and control systems that constitute the Air Traffic Management (ATM) system must be in place and play their roles in an orderly manner. The ATM involves procedures, human resources and technologies that interact in order to ensure in a general form that [36]:

1. Safe guidance of aircraft both on ground and in the air is always provided;
2. Airspace is efficiently managed to accommodate the changing needs of the air traffic over time.

When two or more aircraft occupy the same airspace or airport, they are referred to as “air traffic” which needs to be managed at all time during their flight cycle. The ATM system encompasses all the required resources that enable these aircraft to share simultaneously the same airspace and airport as well as ensuring at all times, a safe, efficient and orderly flow of traffic, both on ground and in the air.

In a wider context, as shown in **Figure 7**, the ATM services are typically provided by the Air Navigation Service Providers (ANSPs) who generally also provide other services including Communication, Navigation and Surveillance (CNS) services, Meteorological Services (MET) and other ancillary services such as Aeronautical Information Services (AIS) [37]. As illustrated in **Figure 7**, to ensure that the above services provides conducive operational environment for all Airspace Users (AUs), they are regulated and supervised at national and international levels by regulatory bodies and supervisory agents. Therefore, the ANSPs, AUs and regulatory and supervisory agencies are the three main ATM stakeholders. Other ATM stakeholders who are not discussed in details in this thesis are the airport operators (see Section 2.5). The ATM system can then be seen as a complex system, involving several stakeholders who sometimes may have conflicting objectives. The ATM stakeholders are further discussed in Section 2.5.

As shown in **Figure 7** and introduced in Section 1.1, the three main subsystems of ATM system are Airspace Management (ASM), Air Traffic Services (ATS) and Air Traffic Flow and Capacity Management (ATFCM). These subsystems perform different functions at different planning layers involving different agents/organisations to achieve the overall ATM objectives. In order to perform their functions, they are supported by several CNS and information technologies as illustrated in **Figure 7**. Consequently, the ATM is also often described as a socio-technical system.

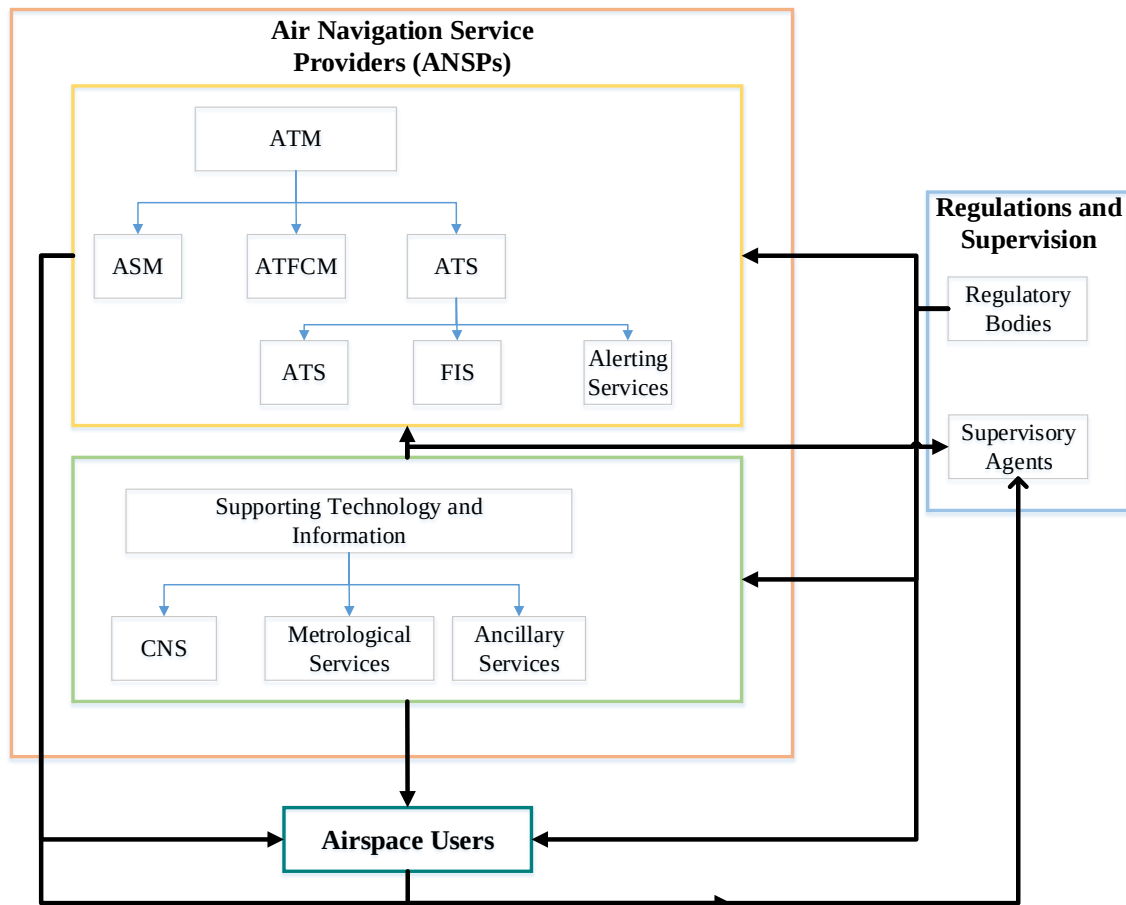


Figure 7: The ATM context

In order to understand the fundamentals of current ATM system and to identify its challenges, limitations and the resulting implication on the ATFCM Demand and Capacity Balancing (DCB), the following sections describe the current ATM functions and roles, interests and concerns of its stakeholders. The ATM technological enablers are discussed in Section 2.7.

2.2 Airspace Management

The ASM functions are performed at the first planning layer of ATM system (strategic and pre-tactical levels), as previously shown in **Figure 1**. They include all tasks related to the planning of airspace infrastructure and its organisation. These tasks according to ICAO [38], include configuration and categorisation of airspace, definition of air routes based on the available navigation aids (NAVAIDS), sectorisation of airspace into ATC sectors and coordination of civil and military control routes.

The ASM functions are usually performed way in advance before the day of operation (typically more than six months before the day of operation) [38], they are complemented by the ATFCM and ATS at later ATM planning and execution layers.

The airspace sectorisation task aims to design ATC sectors⁸ in such a way that each ATC sector can be reasonably managed by a dedicated ATC unit (see Section 2.3 for ATC unit). This is in order to maximise the airspace capacity in the presence of current and forecasted constraints [36]. On the other hand, air routes are configured to reduce the intrinsic risk of aircraft conflicts.

Each Air Traffic Service (ATS) route⁹ in the conventional route network has been defined, driven by aircraft dependency on a sequence of ground-based NAVAIDS required for aircraft navigation. The ATS route is defined by a sequence of segments defined by the positions of these NAVAIDS [39]. They often represent crossing points in the network, where multiple aircraft converges to them.

To organise the traffic flow in the vertical plane and reduce the risk of aircraft conflicts in the network, the ASM have applied the so-called “Semi-Circular Rule (SCR)” in the

⁸ ATC Sectors are 3D volumes of airspace whose shape and capacity may vary over time.

⁹ An ATS Route is a specified route designed for channelling the flow of traffic as necessary for the provision of air traffic services. The term “ATS route” is used to mean variously; airway, advisory route, controlled or uncontrolled route, arrival or departure route, etc.

definition of ATS route network [39]. This rule allows a Flight Level (FL) selection as a function of aircraft heading, applied to facilitate vertical separation between aircraft flying in the opposite direction. In its global default form, SCR allocates an East/West orientation of FL parity. This means that for flights flying under Instrument Flight Rules (IFR) in level cruise flight, the FL number for aircraft with magnetic tracks between 000° and 179° must be odd and the FL number for aircraft with magnetic tracks between 180° and 359° must be even [39]. This provides the basic 1000 feet vertical separation between opposite west/east tracks, reducing the possibility of conflicts.

Figure 8 shows an example parity of SCR for provision of aircraft vertical separation. Opposite aircraft flying East/West tracks are separated assuming the Reduced Vertical Separation Minima (RVSM) rules [40], requiring 1000 feet minimum vertical separation for FLs (FL290-FL410 inclusive). Given that the proposed ATFCM method in this thesis targets the European Civil Aviation Conference (ECAC) airspace, where RVSM rules are applied, the basic separation provided by the SCR is assumed sufficient to provide the required vertical separation in this thesis.

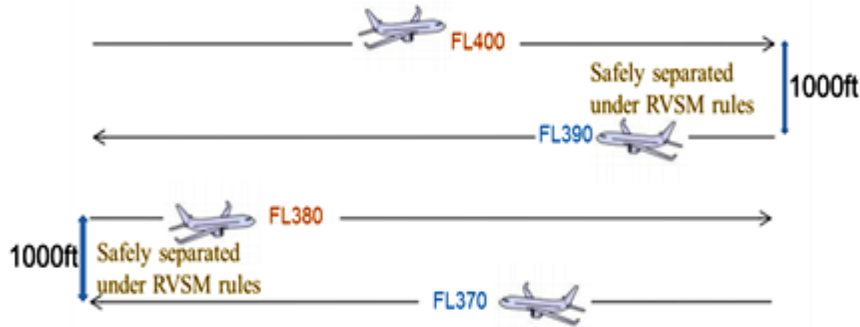


Figure 8: Example parity of SCR for aircraft vertical separation

Despite the above safety measures taken at ASM level, the current route and airspace design especially in Europe remains one of main bottlenecks of ATM system. This is mainly due to its rigid structure, fragmentation and non-optimal ATS routes designed based on the location of aforementioned NAVAIDS [37].

Several research efforts have been made over the years, of which some mainly focus on optimising the route network [41][42][43], others focus on determining the best airspace

configuration given a particular ATS routes configuration [44][45]. A review of these research efforts is provided in Section 2.6.3.

The common agreement in the ATM community and current research initiatives is that the current route and airspace design must be revised, in order to increase the network performance in terms of airspace capacity and flight efficiency and to accommodate future traffic demand [25]. EUROCONTROL suggests that new initiatives for route and airspace design should target on achieving an efficient, flexible and dynamic airspace structure, which enables multi-option routings such as direct routing and Free Route (FR) operations as well as an adaptable and seamless ATC sectorisation [46].

Recent developments in navigation system technologies such as Global Navigation Satellite System (GNSS) which can be integrated into on-board Flight Management System (FMS), enables aircraft to navigate without dependency on terrestrial based NAVAIDS [38]. These technologies are the main enablers of the required change in the airspace design. The aforementioned concept of direct routing is a result of these developments, enabled by the area navigation (RNAV) which allows aircraft to define waypoints in their flight plans that are not associated to the ground based NAVAIDS [25]. The Free Routing Airspace (FRA) concept, currently under development in Europe, is typically an extension of the direct routing concept [11]. The FRA concept is further discussed in Section 2.7.4

2.3 The Air Traffic Services

The ATS consists of all facilitating tactical services required for the safe execution of a flight. According to ICAO [38], these include the Air Traffic Control (ATC) system, the Flight Information Services (FIS), alerting and other advisory services. Whilst all the above elements of the ATS system are important for the ATM, the ATC system is the most relevant for this thesis. Details on the rest of ATS elements can be found in [38].

2.3.1 The Air Traffic Control System

The ATC is responsible for maintaining separation standards between aircraft, preventing collisions between aircraft and between aircraft and other obstructions and

expediting and maintaining an orderly flow of air traffic [12]. To accomplish this hefty responsibility, the ATC system's activities involve procedures, equipment and skilled personnel that interact to perform different functions. These functions include Traffic Synchronisation (TS), Separation Management (SM) and Collision Avoidance (CA) [47].

Since the aircraft is controlled in all phases of flight, the ATC are normally organised into aerodrome control; provided by the Aerodrome Control Tower (TWR), approach control; conducted by the Approach Control Unit (APP), and the area control; administered by the Area Control Centres (ACC) [38]. **Figure 9** shows the airspace organisation from ATC control perspective.

At aerodromes, local TWR ATCOs issue landing/take-off clearances and manages ground movements between gates and runways when aircraft are on the runways and their vicinity. From TWR ATCOs, the flight is assumed or handed over from/to the APP ATCOs who manage the sequencing of arriving/departing flights during descent and climb phases of flight, typically up to the transition altitude. When a flight has reached higher altitudes, it is controlled by the ACC. There are elementary sectors within one ACC. A flight normally transit through these sectors (within the same ACC, or between adjacent ACCs) until it's handed over to the APP.

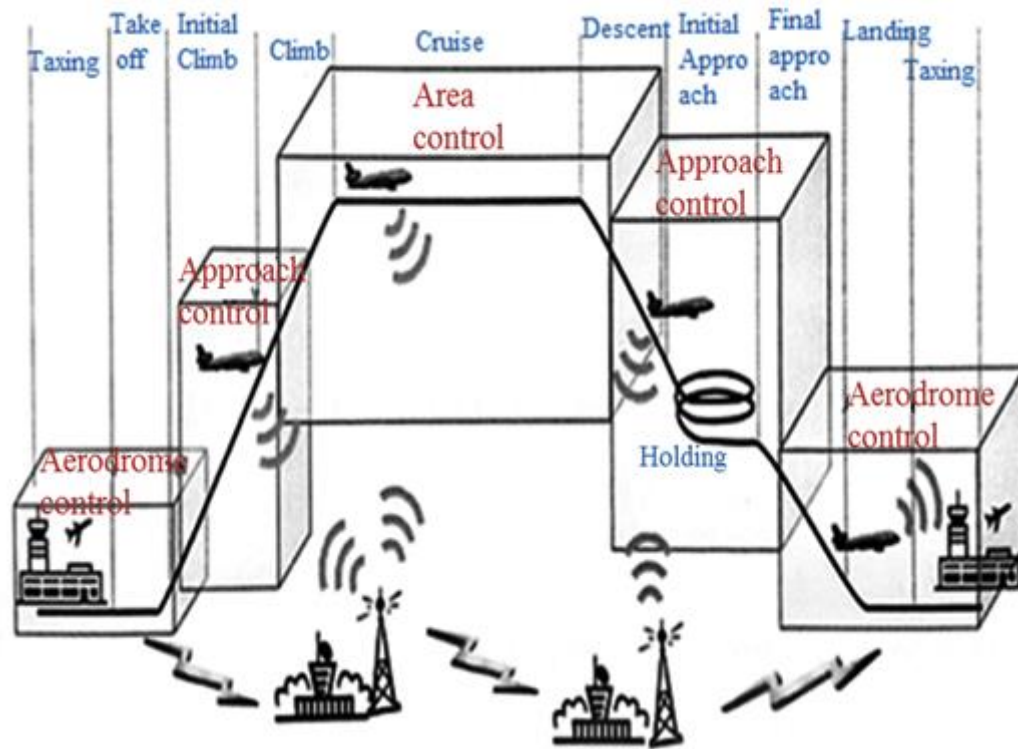


Figure 9: Airspace organisation from ATC control perspective [48]

This thesis focuses on mitigating conflicts only in the en-route phase of flight. Therefore, only ATC roles in en-route phase, performed by ACC ATCOs, are discussed further in this section.

An ACC ATCO endeavours to ensure, safe separation for all aircraft in the sector at all times as well as handing over or assuming traffic to and from adjacent sectors. In general, in all ACC sectors, the roles demanded of each ATCO include [36]:

1. Assuming responsibility of aircraft entering sector under his/her control;
2. Estimating future positions of aircraft and detecting any conflicts between them;
3. Intervening to provide sufficient separation between aircraft where conflicts exists;
4. Transferring aircraft exiting his/her sector of control to the adjacent ACC and or APP sectors.

To perform all the above roles, ATCOs have to do demanding mental work. However, among all the above roles, it is widely acknowledged that the ATCO workload more correlates with their interventions related to aircraft SM (roles 2 and 3 above). The ATCO SM interventions are required to ensure that sufficient separation between aircraft is maintained. The sufficient separation between aircraft is defined by certain predetermined separation minima standards [40]. These ATCO SM interventions nowadays are considered the main bottleneck of the current ATM system. For the sake of completeness of the exposition, it is necessary to elaborate on them further in the following section.

2.3.2 The ATC Separation Management Function

Different ATCOs' tactical intervention tasks that constitute the ATCO SM function are summarised by the schematic shown in **Figure 10**.

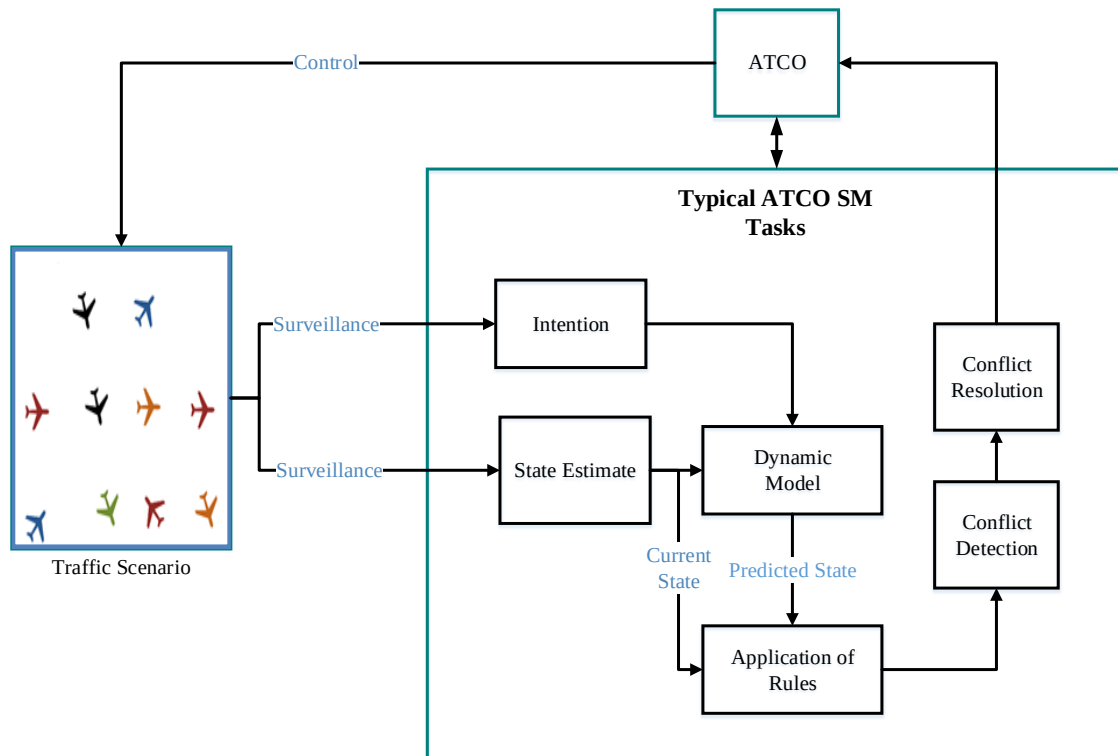


Figure 10: ATCO separation management related tasks

As illustrated in **Figure 10**, for a given air traffic scenario, ATCOs monitor the current state and the intention of all aircraft in their sector of responsibility. This task is usually

achieved through radar surveillance and radio communication [49]. Then, ATCOs must predict the future aircraft state in order to detect for any conflicts. For ECAC en-route airspace (see Section 2.4.1), conflicts are detected by applying a standard en-route separation minimum of 5 NM for horizontal separation and a minimum of 1000 feet for vertical separation [50]. If any conflicts are detected, ATCOs must issue over voice and or data channels, resolution clearances to the involved aircraft and must monitor aircraft to ensure the correct execution of these clearances.

The ATCO conflict resolution clearances or techniques involve heading change/track change, altitude change and speed change manoeuvres. A comprehensive review of the above different ATCOs' conflict resolution techniques is provided in [51], where it is shown that the majority of the current ATCO resolution clearances are issued in form of heading and altitude change manoeuvres. It is for this reason that most of existing research efforts have developed conflict resolution models that are essentially based on these two manoeuvres [51].

Heading and flight level change techniques can more effectively remove a loss of separation than speed control [51]. Consequently, they are more suitable when it comes to resolving conflicts in ATC tactical/reactive situations. However, these reactive techniques are essentially used to ensure flight safety but at the expense of flight efficiency, since they usually result into inefficient manoeuvres in terms of fuel consumption and flight time, increasing AUs' operational costs [51]. Nevertheless, the reactive nature of the current ATM system drives the conflict resolutions in favour of these reactive techniques over speed control [52]. This preference is practically manifested since current aircraft conflicts are only locally and tactically detected. Speed control requires significant anticipation time to resolve conflicts. This is due to limited possible speed changes that can be achieved, that are compatible with aircraft performance.

Since this thesis focuses on detecting conflicts far in advance, at pre-flight phase when there is enough anticipation time, speed control will be applied to resolve them proactively. This will enable to deliver a de-randomised and well-behaved (conflict free) traffic to the ATCOs at tactical level, reducing their workload.

2.4 The Air Traffic Flow and Capacity Management System

The ICAO defines the ATFM system as “a system established with the objective of contributing to a safe, orderly and expeditious flow of air traffic by ensuring that ATC capacity is utilised to the maximum extent possible, and that the traffic volume is compatible with the capacities declared by the appropriate ATS authority” [53].

In Europe, the classic ICAO Air Traffic Flow Management (ATFM) system has evolved towards the integration of capacity management which resulted into the new concept of “Air Traffic Flow and Capacity Management (ATFCM)”. Hence, the ATFCM objective is “to optimise the usage of available capacity (ATFCM)” and “to adapt the excess of demand to the resulting capacity (classic ICAO ATFM)” [54].

The ATFCM performs all the pre-flight activities required to balance the air traffic demand with airspace/airport capacity. This balance is required to optimise air traffic flows and avoid overloading ATCOs’ workload, while minimising deviations due to congestion and other traffic flow constraints imposed on the AUs’ preferred trajectories [54].

2.4.1 The ATFCM Demand and Capacity Balancing Function at a Glance

In Europe, the ATFCM Demand and Capacity Balancing (DCB) function is performed by the Network Manager (NM), which centrally manages the ATFCM for all the 44 states participating in the ECAC area [55]. **Figure 11** shows the map of the ECAC area.



Figure 11: European Civil Aviation Conference area [56]

Current NM DCB activities are performed at different ATM planning levels as discussed below [54]:

At strategic level: Through the evaluation of future air traffic demand scenarios, the NM Operations Centre (NMOC) assists each ANSP in the ECAC area to predict what capacity might be needed in each of their respective Air Traffic Control Centres (ATCCs) to accommodate the anticipated traffic demand. At this level, a particular routing scheme may be prepared to maximise the airspace capacity to better allocate the anticipated traffic demand. Irregular events such as military exercises and sports events scheduled to occur more than one week in the future are considered at this planning level for DCB planning purposes. At the end of this planning level, the capacity commitments made by all ANSPs are published by the NM in the Network Operations Plan (NOP) portal¹⁰.

At pre-tactical level: The NM gathers from various sources, different information such as the declared capacity of different ATCCs, early flight schedules, weather forecasts and other notices to airmen. This information is used to define the daily plan. A daily plan includes all the anticipated ATFCM regulations for the following day. This then is published in the NOP portal one day before the flight.

On the day of operations: When new DCB constraints are detected on the day of operations, the NM attempts to maximise the capacity by rebalancing the equilibrium between capacity and demand through the implementation of ATFCM regulations. The regulation may be imposed in form of ground delays, re-routing (new aircraft trajectory) and by assigning aircraft new take-off times or a combination of the above. The implemented regulation(s) then becomes the available NM's "control action", applied to limit the maximum rate of aircraft entering either a regulated volume of airspace or

¹⁰ The Network Operations Portal (NOP) is a Eurocontrol single collaboration and planning tool, which allows a common view of the European ATM network situation to be shared with the whole aviation community. It is a means of interactively accessing the European ATFCM network situation, which incorporates the existing information and Airspace user's requests, provides traffic demand and capacity plans, identifies bottlenecks, and presents the ATFCM and ASM measures planned in order to counterbalance them [54].

airport. The main objective of regulations is to maintain ATCOs' workload to reasonable levels while at the same time trying to minimise deviations to the AUs' desired FPLs.

The following section reviews the performance of ATFCM ground delay and re-routing regulations, whereas a review of ATFCM take-off time slots reallocation regulation is discussed in Section 2.6.2.

2.4.2 The Performance of the Current ATFCM Regulations

The ground delay regulation, is applied to decrease the entry rate of flights into sectors and/or airports where the arrival traffic demand is expected to exceed capacity [57]. On the other hand, the re-routing regulation involves assigning new routes to some aircraft which are different from those initially preferred by the AU, in order for those aircraft to bypass the congested sectors [58].

The underlying rationale of ground delay regulation is that if airborne delay is unavoidable, it is economically cheaper for AUs and safer for aircraft to absorb that delay before take-off. Ground delay is the most applied regulation and often preferred over the re-routing regulation. This is mainly due to higher fuel consumption often associated with the later [59]. However, from an ATC perspective; ground delays are often problematic because they may cause congestion at departure airports [60].

In addition, the current algorithms for computing ground delay assignment have shown several irregularities [58]. This is mainly due to their difficulty in accurately computing the duration of the ground delay regulation and in deciding which aircraft to be affected by it [58]. Consequently, the ground delays have often resulted into saturations and sometimes idleness of the airspace and airport resources due to the system's uncertainties [58]. Idleness usually occurs when the predicted demand and expected capacity constraints that prompted the ground delay regulation does not materialize, whereas saturations may occur when aircraft increase their flight speed in order to recover some of the time lost during ground delay to compete for arrival slots which are currently assigned on a First Come First Served (FCFS) basis. This often aggravates the congestion situation in sectors and/or arrival airports which in turn overloads the ATC workload [61].

Occasionally, the re-routing regulation is necessary. This happens in situations where significant capacity constraints are expected only in en-route sectors whilst departure and arrival airports are still operating within their capacity limits. In this situation, the NM may ask the local ATCCs to accept flights that were initially not planned to route through their sectors to enable some traffic to avoid severely capacity-constrained sectors [62]. However, in peak times, the receiving sectors of the rerouted flights may also already be operating at or near their capacity; thus, re-routing may lead or aggravate congestion in those sectors. In addition, current re-routing routes often results in relatively longer trajectories compared to those initially desired by the users [62]. This makes re-routing regulation highly suboptimal in the AUs' perspective.

It is evident that, in the en-route sectors, the ATFCM activation of the above regulations is based on the limitation of the maximum number of aircraft that can simultaneously enter a sector (sector count) and/or within a sector (occupancy account) for a given time period without any consideration of conflicts involved. This causes a discontinuity at ATFCM level in the current ATM safety layers. This discontinuity is discussed in Section 2.4.3 below.

2.4.3 Discontinuity in the Current ATM Safety Layers

In Section 1.2.2, flight efficiency and flight safety have been discussed as being the two ATM system's invariant objectives. However, the overriding objective of the ATM system is to ensure safety by avoiding aircraft conflicts at all time. This is nowadays achieved through different safety layers of the ATM system that exist at different ATM pre-flight planning and tactical layers. **Figure 12** shows the ATM safety layers, defined with respect to the available time to react before a conflict occurs.

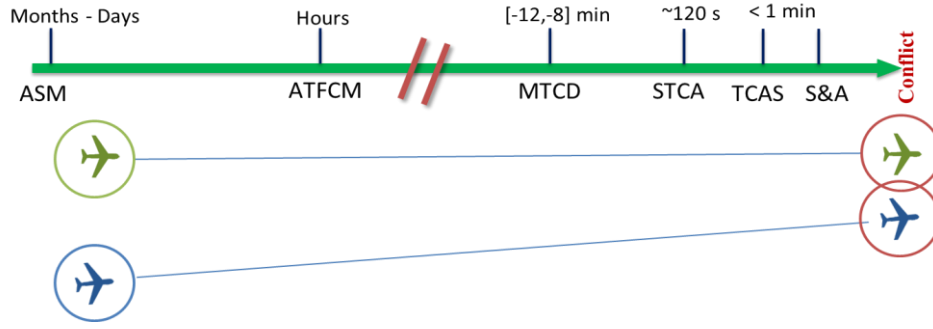


Figure 12: ATM pre-flight planning and execution levels' safety layers

As shown in **Figure 12**, a few seconds before Mid-Air Collision (MAC), the last safety layer “See-and-Avoid (S&A)” exists [63]. In less than a minute before the collision, Traffic Alert and Collision Avoidance System (TCAS) on-board aircraft becomes the second safety layer. TCAS provides traffic alerts and resolution advisories to aircraft involved in potential MAC [64].

Within a few minutes before the conflict, the ATC system is supported by the Short Term Conflict Alert (STCA) and Medium Term Conflict Detection (MTCD) Decision Support Tools (DSTs), which detects and alerts ATCOs about aircraft conflicts. They provide additional ATM safety layers at tactical level [65].

At pre-flight planning layer, the ASM system helps to reduce the probability of conflicts by structuring the ATS route network, providing the first ATM safety layer. As discussed in section 2.4.2, a safety problem then manifest at ATFCM DCB level because the current ATFCM is only focused on maintaining reasonable ATCOs' workload through control of aircraft sector entry count and or occupancy count performed with no consideration of conflicts, thus, causing a discontinuity in the current ATM safety layers as illustrated in **Figure 12**.

From the above discussion, clearly all other ATM planning and tactical levels except ATFCM DCB level, provides safety layers that are devoted to minimise/remove aircraft conflicts. The position of this thesis is to reformulate the ATFCM DCB function in order to include the same criteria used in other ATM planning and tactical levels. In other words, to include a safety layer that enables to minimise aircraft conflicts at

ATFCM DCB level, bridging the aforementioned existing discontinuity in the ATM safety layers.

2.5 The ATM Stakeholders

2.5.1 The Main Composition of ATM Stakeholders and their Responsibilities

The ATM system has four main stakeholders; the AUs, ANSPs, regulatory and supervisory authorities and Airport Operators. A brief description of each is provided below.

The airport operators: Airport operators are typically responsible with the airport terminal and airside ground operations. They provide facilities and necessary services required by the AUs at the airport including ground-handling services such as baggage handling, refueling and firefighting services. Since the research problem in this thesis only covers ATM operations in the en-route phase of flight that is beyond the airport limits, the airport operators are not discussed further. Further details and description of roles of this stakeholder can be found in [66].

The Airspace Users: The AUs includes both civil and military air transport. In Europe, AUs are classified as either General Air Traffic (GAT) or Operational Air Traffic (OAT). The GAT encompasses all flight operations including civil, commercial, state aviation and all other flights conducted in accordance with ICAO rules and procedures, whereas the OAT consists of military traffic and Unmanned Aerial Vehicles (UAVs) which do not follow ICAO rules and procedures [67].

Both GAT and OAT flights are further classified based on their navigation capabilities in different weather conditions, where some aircraft operates under Visual Meteorological Conditions (VMC) and others operate under Instrument Meteorological Conditions (IMC) [67]. In VMC, aircraft operates under Visual Flight Rules (VFR) that requires pilots to depend on outside reference visual cues for navigation, orientation, and separation purposes [67]. In the case of IMC, Instrument Flight Rules (IFR) applies, where ATC is responsible for the provision of separation services [67]. Consequently,

all IFR flights must have an approved detailed FPL defined following departure; en-route and arrival specific instrument procedures that are commensurate with IFR procedures (see Section 2.6 for flight planning process).

This thesis concerns on GAT under IFR flights which predominantly operate in the busiest airspaces such as the ECAC airspace, where en-route capacity constraints typically occur.

The Air Navigation Service providers: The ANSPs are public or private entities that manage the air traffic on behalf of a state or a region [50]. All ATM services are normally provided by individual ANSP who operates locally in different countries with a few exceptions such as in Europe where several ATM functions are currently provided by a centralized organization, namely “the EUROCONTROL” with its special centralised function “the NM” carrying out most of the ATFCM functions at a regional level. The ANSPs’ primary role is to ensure the availability of navigable routes for AUs within the regulated and controlled airspace [9]. A controlled airspace is a volume of airspace, where air traffic is controlled under the authority of a particular ANSP.

Regulatory and Supervisory Agencies: Regulatory and supervisory agencies in general include international organizations such as ICAO and National Supervisory Authorities (NSAs) [36]. They are particularly responsible for certifying and overseeing ANSPs as well as for the preparation of deferent aviation performance plans. For ATM in particular, they help to ensure that ATM operations are conducted in accordance to the agreed international, regional and national standards and procedures. This is important in ensuring that standardized and fair ATM services are provided to all AUs, and to ensure the ATM system continues to develop for the benefit of all its stakeholders. At international level, ICAO codifies and fosters the planning and development of the ATM system to ensure safe and orderly growth of the air transport industry at a global scale. The ICAO technical annexes (Annex 2 [68] and Annex 11 [36]) and ICAO Doc 4444 “Procedures for Navigation Services-Air Traffic Management (PANS-ATM)” which documents a technical manual [38], specifies in detail the fundamental requirements of the ATM system that each state must provide in its territory. These documents also specify provisions and procedures relating to the safe management of

ATFCM. In response to the current ATM challenges discussed in Section 1.2.1, ICAO has defined a global ATM operational concept, from which different regional initiative programmes such as SESAR and NextGen have adopted to particular characteristics of their areas in developing their respective ATM CONOPS targets [9][37], as discussed later in Section 2.7.

The Link: In order to achieve smooth ATM operations, the ANSPs, AUs and regulatory authorities must collaborate as much as possible. Moreover, it can be understood that ANSPs are the ATM service providers and AUs (mainly airlines) are the customers, whilst the regulatory agencies implement autonomous authority over them to ensure standardisation and a certain degree of fairness.

The majority of the world's ANSPs are members of the Civil Air Navigation Services Organisation (CANSO) [69]. Similarly, more than 90% of the civil airlines are members of the International Air Transport Association (IATA) [70]. These associations aim to represent interests and concerns of these two major ATM stakeholders in the global ATM community and other forums such as ICAO regulatory forums. Their ATFCM DCB interests and concerns are elaborated on in Section 2.5.2 below.

2.5.2 Interests and Concerns of ANSPs and AUs in ATFCM DCB Function

The main interest of the ANSPs is to meet their ATM objectives and the associated operational requirements whilst at the same time being able to recover their investment through the provision of air navigation services to AUs [37]. Derived from this interest, apart from the invariant safety concern, ANSPs are currently concerned with the traffic growth and delays that have significant negative impact on their quality of service [17]. On the other hand, AUs main interest is to fly their desired flight plans, minimising their operational costs by reducing flight time, fuel consumption and flight delays [71].

AUs' concerns can be seen in light of weaknesses spanning at different planning levels of the current ATM system. At strategic level, the current design of the European route network demarcated by the ASM system is sub-optimal which leads to high aircraft fuel consumption [72]. At pre-tactical level, ATFCM regulations often cause aircraft costly delays especially in high-density airspace areas and busiest airports (see Section 1.2.1).

At tactical level, the current ATC tactical interventions to avoid conflicts often result in increased flight distance and flight time which directly affect the flight operational costs and crew workload [73]. Furthermore, these tactical interventions are not currently predictable and their number is expected to increase with the traffic growth [73].

From the highlighted ANSPs' and AU's ATFCM interests and concerns, it can be seen that although the two stakeholders may have different interests, they do share some major invariant concerns. These concerns can be summarized as:

1. Flight/network inefficiency due to ATFCM DCB inefficiency and associated ATC tactical interventions;
2. Lack of airspace capacity resulting into congestions and delays;
3. Safety concerns.

In order to mitigate the above concerns, this thesis proposes changes in the current ATFCM DCB function. The proposed initiative of identifying and mitigating conflicts at pre-flight phase leads to a reduction in the number of current ATC interventions, which have positive effects on both ANSPs and AUs, hence, this initiative is likely to be adoptable in the future ATM operations. There are various expected benefits of the new ATFCM DCB method proposed in this thesis for both ANSPs and AUs as discussed below.

As the new method provides measures to ensure safe separation of aircraft trajectories at conflicted junctions (crossing and merging points) before flight, it implies that in most cases, ATCOs will not have to issue separation maneuvers to aircraft at those points anymore. This could reduce ATCOs' workload at constant traffic levels or enable them to accommodate traffic increase at constant workload. In the latter situation, a great amount of the ATCOs' workload could be transferred from tactical separation tasks to traffic monitoring, hence, reducing their mental workload demands. Whilst, in the former situation, the available ATCOs' workload can be used to increment the airspace capacity; enabling the airspace to accommodate new flights or even to accommodate some flights that are currently delayed due to congestion. Hence, ANSP revenues should be expected to increase.

For AUs, the reduction of ATC separation interventions implies diminution of aircraft manoeuvres. This could lead to fuel consumption reduction, enhancement of flight punctuality as the delays induced by manoeuvres decrease, and improved predictability as flights follow their planned trajectory with fewer modifications.

2.6 Review of Current DCB Process

2.6.1 Current Evolution of a Flight Plan from Airspace User's Business

Intent

The flight operation is characterised by high fixed flight operating costs and direct flight operating costs [11]. All airlines strive to produce flight plans that meet their overriding interest being as stated in Section 2.5.2 “minimizing direct operating costs whilst maximising their incomes”. The direct operating costs can be minimised through the optimisation of flight time, fuel consumption and through minimisation of ground and airborne flight delays [74]. To try to minimise their direct flight operating costs, airlines have to work at different flight planning levels spanning from strategic to tactical levels and involving multiple agents [75]. Therefore, the execution of a flight “the actual flown FPL” is a result of a long and complex process, which involves complex interactions between different flight operations agents and interactions between these agents and other ATM functions, at different flight planning levels.

To manage efficiently these complex interactions, most airlines typically coordinate their flight planning activities and other daily operations at centralized Flight Operating Centres (FOCs) [75]. To perform its duties, FOC's interact on behalf of airlines with the NM, airport operators and with individual pilots. FOCs must compute optimal FPLs for all of its scheduled flights and ensure that each flight is executed efficiently [75].

Figure 13 provides a generalised summary of the main FOC's duties.



Figure 13: The main duties of FOCs

The first and second of the FOC’s duties in **Figure 13** “aircraft or mission scheduling and flight planning” are complex optimisation problems; they are driven by many constraints and uncertainties. Their major drivers however, are the economic situation, airline strategy and the market-estimated demand [75].

The mission scheduling commonly referred to as flight scheduling is a multi-objective problem. This is because FOCs must try to maximise the use of airline’s fleet while at the same time using buffers to ensure flexibility in the scheduling process to better deal with various ATM system’s uncertainties [76]. Consequently, FOCs may apply techniques such as delay absorption buffering, which leads to a trade-off between the cost and robustness of the solution [77]. For details on the flight-scheduling problem, the reader is referred to [78], where a comprehensive description of the flight-scheduling problem in presence of uncertainty is provided.

Regarding the flight planning process, **Figure 14** shows a generalised optimisation scheme applied by FOCs to produce a FPL for each flight. From **Figure 14**, clearly, the Cost Index (CI) is an important component of the flight planning optimisation, it enables weighting the cost of time against the cost of fuel through the objective function “ $J = \text{Fuel} + \text{CI} \times \text{Time}$ ” solved for each flight [79].

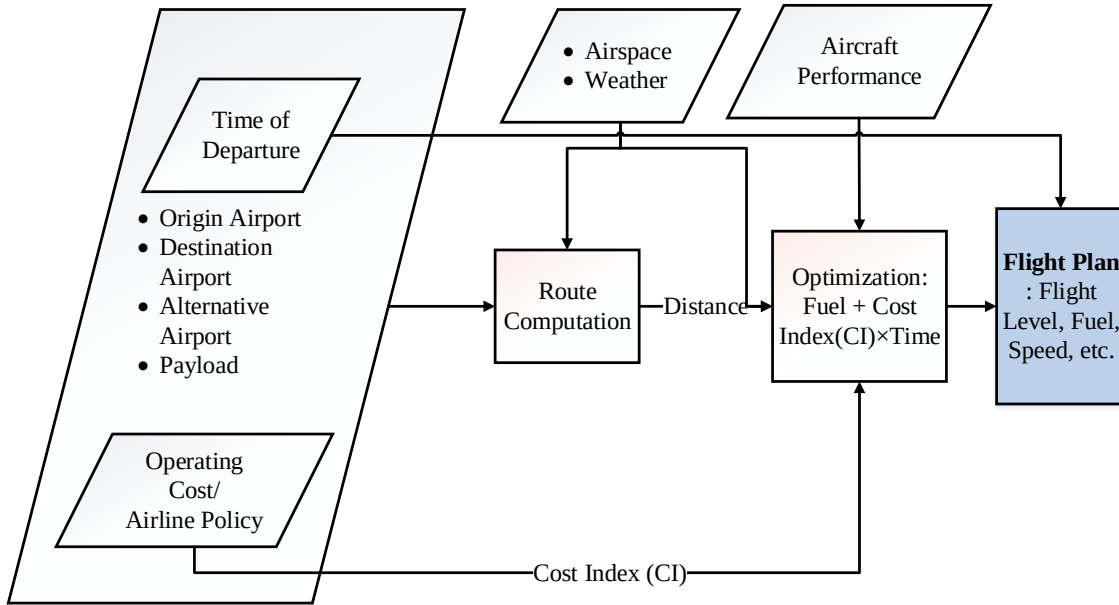


Figure 14: The generalised FOC's flight plan optimisation Scheme

Although the above objective function is the same across different FOCs, their mission/business intentions are proprietary and vary from one AU to another; as a result, their preferred CI values also varies [79]. For instance, one AU may prefer timely flights to avoid missed connections whilst the other may prefer fuel saving routes over time concerns. Considering these variations in CI preferences, care is taken in this thesis to ensure that AUs' CI is unaffected by the proposed methods.

When FOC has determined a flight schedule usually a few days before the estimated time of aircraft departure, the schedule is entered into airline's internal Initial Flight Plan Processing System (IFPS) to produce an Initial Flight Plan (IFPL) that meets interactive standard format "the ICAO format" [80]. The ICAO formatted IFPL is sent to the NM. The NM then performs syntax and consistency checks on all the filed IFPLs. If there is any IFPL with inconsistency, it is either rejected or in case of minor inconsistencies manually processed by the NM [80]. **Figure 15** illustrates the Initial Flight Planning Process.

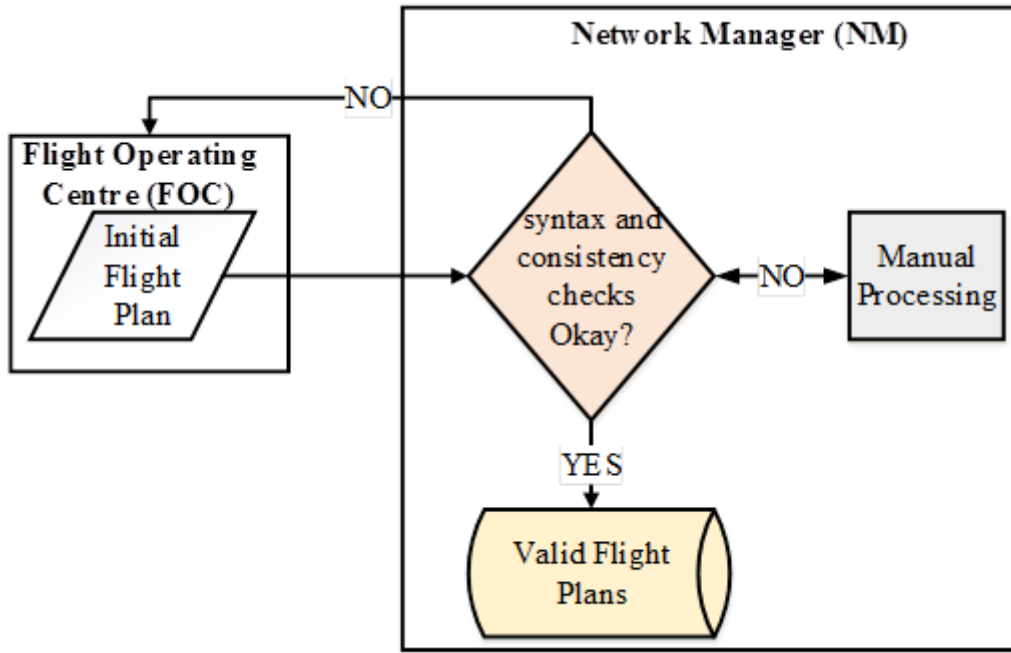


Figure 15: Initial Flight Planning Processing[54]

Currently, the NM receives on average approximately 35000 IFPLs each day, of which about 9% have to be revised to remove inconsistencies [81].

2.6.2 The Evolution of Flight Plans to NM's DCB Problem

Using the data for all the filled FPLs and the declared capacity of different ATC sectors and airports in the whole ECAC area, the NM tries to detect for any imbalance in the network [80]. For those locations where the imbalance is detected, the NM in coordination with Flow Management Positions (FMPs)¹¹ may decide to suggest re-routings and or activate other ATFCM regulations. At this stage, the NM coordinates these ATFCM regulations through FMPs to the affected ACCs, APPs and TWRs [54].

Figure 16 shows the current flight planning and NM's DCB process.

¹¹ An FMP is a working position established in appropriate ATC units to ensure the necessary interface with a central management unit on matters concerning the provision of the air traffic flow management service. It is an interface between ATC and the NMOC established in the States within, and adjacent to, the ECAC area [84].

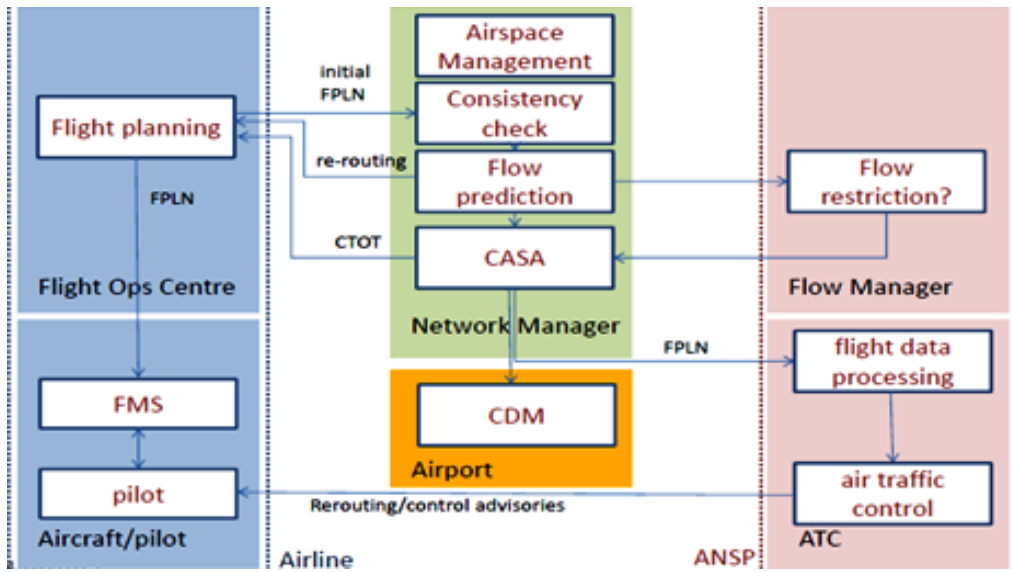


Figure 16: Flight planning process and NM DCB process

When regulations are activated, the associated capacity constraints (sector entry count for en-route phase of flight) of the affected sectors required to avoid ATC workload overload are translated into a limited number of runway take-off slots [55]. The process of allocating these limited take-off slots to flights is performed by a greedy dynamic algorithm “the NM Computer Assisted Slot Allocation (CASA)” [55]. For FPLs of all flights planned to enter regulated locations, CASA re-computes their Estimated Take-Off Times (ETOTs) and builds a list of new Calculated Take-Off Time (CTOT) slots “the Slot Allocation List (SAL)”. The SAL is built based on the rate of required sector entry count. For example, a regulation lasting four hours, associated with a basic rate of 28 flights per hour arriving into a sector, would result in a SAL with 112 slots separated from one another by approximately 2 minutes.

Each flight is allocated a slot in accordance with the “First Planned-First Served (FPFS)” principle, which presumes that flights should be sequenced to arrive over the regulated location in order they would have arrived in the absence of any regulation [55]. The allocated slots are however, provisional and subject to amendments. When CASA receives new flight plans, it tries to pre-allocate slots to respect the entry count threshold.

The CASA algorithm has several limitations. For instance, in situation where an aircraft is subjected to several ATFCM regulations, it is allocated the delay corresponding to the most penalising regulation; this may however, lead to capacity constraints violation in other sectors crossed by the same flight. In fact, it is largely acknowledged that in high-density situations, the CASA solution have very small or sometimes no effect on ATCOs' workload [82],[83].

Furthermore, the CASA system is largely centralised such that it functions in passive mode from AUs' point of view. Indeed, the act of filing a FPL currently only ends with a request for a slot from AUs' to NM, and the NM unilaterally decides on how to resolve DCB issues with no input from the AUs. In the past, when congestion densities were low, airlines could reasonably absorb flight delays with limited effects on the integrity of their flight schedules. However, with the current and future high-density situations in sectors, as demand levels approximate available capacity, even minor disruptions may have significant ripple effects and lead to sustained periods of congestion. This necessitates new ATFCM DCB solutions that provide both minimum network effects on the system and minimum impact on the integrity of AUs' desired FPLs. Therefore, coordination and cooperation between the NM and the AUs will be extremely important in the future to achieve effective DCB solutions. Such a coordination and cooperation is the basis of the SESAR Business Trajectory (BT) concept (see Section 2.7), which is a major enabler of the methods developed in this thesis as discussed in Section 2.7.3.

It is understood in this thesis, that CASA algorithm limitations are not the only cause of inefficiency seen in the current ATFCM DCB solutions, but also the metrics and processes applied to estimate and manage the operational airspace capacity and operational air traffic demand limits the effectiveness of these solutions. These metrics and process are discussed in Section 2.6.3 and Section 2.6.4 for airspace capacity and traffic demand respectively.

2.6.3 Re-configuration Schemes for Determination and Management of Airspace Capacity

Sector re-configuration scheme is a method applied at ATCC level to manage the airspace capacity [84]. This method is applied in synergy with NM's regulations for DCB management. Sector re-configuration schemes are performed in order to adopt the airspace capacity to the expected traffic demand and to anticipate possible congestion issues before the NM slot allocation process begins. The filled FPLs and the declared capacity of the sector re-configuration schemes are the two main inputs to the CASA slot allocation algorithm, where the filled FPLs reflect the expected traffic demand, whilst sector re-configuration schemes reflect the expected airspace capacity [84].

Based on the expected traffic demand and the available ATC workforce, the ATCC determines the best combinations of elementary sectors' configuration in order to better adapt to the expected traffic demand. Each ATCC configuration is determined by splitting or combining the elementary sectors over time [85]. Typically, the ATCC have a database of some customary configurations from which depending on the available ATCOs workforce and the expected traffic demand, a particular ATCC configuration is chosen as the most adequate for an anticipated adoption period [85]. Several configurations are usually required in each ATCC throughout the day; a sequence of these configurations is what is referred to as the "sector re-configuration scheme".

Larger sectors are split into smaller sectors to increase the airspace capacity, when high demand is expected. This however, evidently requires extra ATCOs workforce to control the extra sectors. On the contrary, when demand is low, sectors are recombined to be managed by fewer ATCOs. Because of this dynamic reconfiguration of ATCCs, the whole airspace capacity is varied even when the capacity of individual elementary sectors is unchanged [86]. However, in the context of operational capacity management for ATFCM DCB, the re-configuration scheme approach has several limitations. Apart from the aforementioned increase in the required ATCOs workforce, the other limitations discussed in the following paragraphs are identified.

To ensure the safety of flights and to avoid the wastage of resources, the declared capacity associated with each ATCC configuration must not be operationally exceeded. This implies that the re-configuration schemes declared during ATFCM DCB planning timeframe should always be adhered to at operational/execution phase. However, this is usually more hypothetical than it is practically achieved since the actual elementary sector openings do not always adhere to the planned sector opening schedule, due to several reasons such as ad-hoc ATCO staffing shortages and other system's uncertainties [87]. Hence, sector capacities declared for re-configuration schemes hardly approximate the actual operational capacity.

Additionally, to select a particular ATCC configuration from the aforementioned candidate customary configurations, the selection process is based on empirical assessment performed by comparing the total expected entry counts of elementary sectors in each candidate customary ATCC configuration [87]. This enables to pre-define the entry count of each ATCC configuration in order to select a configuration expected to result into the highest throughput [87]. However, the opening of a particular set of sectors, does not guarantee the arithmetic sum of the capacities of the elementary sectors. The combined capacity is a complex combination of factors such as traffic flow direction and number of ATC interventions due to conflicts. Therefore, a capacity figure in terms of sector entry count is a very rough estimate and is not a good criterion for balancing ATCO's workload, particularly in high traffic density situations.

Several research approaches discussed below have been considered in the literature, focusing on the optimisation of sector configurations, but they are yet to overcome the above limitations.

A genetic algorithm that automatically computes a balanced re-configuration scheme of a fixed number of merged elementary sectors of ATCCs, has been proposed to reduce the number of required ATCOs during daily off-peak periods in the French ATC system [52]. The re-configuration schemes are modelled by partitioning a graph into several connected components. The optimisation criterion is based on the minimisation of both the ATCOs' workload within each elementary sector and the coordination workload between adjacent elementary sectors, assuming that all elementary sectors within an

ATCC will be open at the execution level. A hypothetical ATC network with a fixed number of control positions was used as illustrated in **Figure 17**. The algorithm successfully performed an hourly iteration in order to rebalance dynamically the traffic demand to the available capacity. However, since the variation on the number of open sectors was not considered, the results of this approach were considered less practicable.

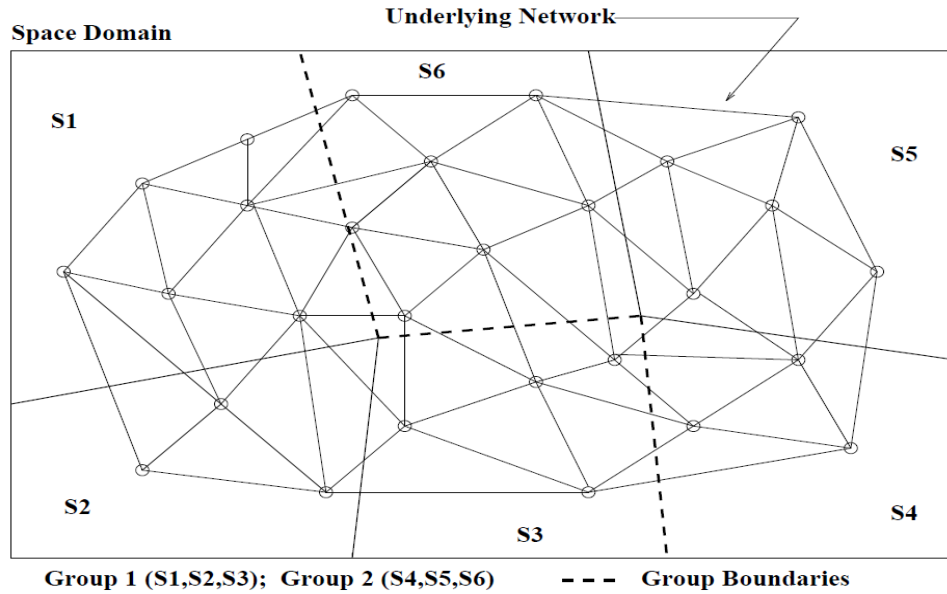


Figure 17: Sectoring hypothetical example [52]

To extend the above study, the hypothetical ATC network in **Figure 17** was replaced with a more realistic new scenario [43]. In the new scenario, actual data from one French ATCC including air traffic data, airspace network data, sector capacities and the number of available control positions were used. Constraint Programming (CP) was used to compute optimal sector configurations based on hourly maximum sector entry count, whilst penalising any sector overloads and underloads to avoid the ATC workload overload and wastage of ATC workforce. The number of the available ATCOs was used as the boundary condition that determines the maximum number of operational sectors for each hourly configuration. It was concluded that the results showed significant reduction in reconfiguration scheme costs in terms of the required number of ATCOs. These results however, as discussed above, were obtained when a set of operationally open sectors were selected from a single French ATCC database.

To extend the scope of the above study, a study using evolutionally algorithms was proposed considering a larger geographic area and a wider set of elementary sectors [87]. In the study, it was investigated how sector configurations could improve the current slot allocation efficiency and concluded that although the algorithms proved to be efficient, the results were too unrealistic to be adopted in real practice. The unrealistic results were attributed to lack of flexibility in the current system caused by the following main two limiting factors:

1. The fact that capacity overload when determined by entry count threshold, may occur in elementary sectors that could not be split any further;
2. The fact that the number of available ATCOs on duty may not be sufficient to open or split as many elementary sectors as would be necessary to achieve optimal solutions.

The above two limiting factors, are the motive of the recent initiatives such as the Dynamic Airspace Configuration (DAC)¹² concept. The DAC concept takes advantage of new advancements in CNS technologies (for new CNS technologies see Section 2.7.4), in order to increase the flexibility of airspace configuration [88][89]. Nevertheless, care should be taken as too much flexibility in the sectors' boundaries and configurations could lead to ATCOs loss of situational awareness.

Moreover, this thesis recognises that the main issue with the current capacity management is not the lack of airspace flexibility, but instead the lack of predictability that leads to variations between the declared airspace capacity and the operational airspace capacity. Therefore, it is the position of this thesis that the focus should be put on the enhancement of the overall predictability of the ATM system. However, caution is taken in this thesis to avoid seeking improvement in predictability by constraining flexibility. This is achieved by focusing on exploiting the current freedom gap between the present-layered ATM pre-flight ATFCM DCB function and ATC tactical management. Delivering stable de-conflicted flights to ATCOs will minimise their

¹² Dynamic airspace configuration (DAC) is a concept proposed to convert airspace sectorisation from the structured and static airspace to a dynamic one capable of accommodating dynamically changing traffic demand.

tactical interventions, while also re-focusing the ATFCM DCB on pre-flight trajectory management rather than flow management. The airspace capacity could then be determined by the number of ATC tactical interventions required for every traffic scenario.

2.6.4 Current Criteria for Determining Operational Air Traffic Demand

As highlighted in Section 2.6.3, currently the expected traffic demand is estimated per ATC sector as the maximum number of aircraft simultaneously entering a sector for a given time period (sector entry count). To establish this number, aircraft expected to enter each sector during this period (typically one hour) is counted [90]. The resulting total number of aircraft is then, the expected traffic demand used for ATFCM DCB. It is this number that is compared to the declared sector capacity to detect for the imbalance between demand and capacity [90]. However, as stated in Section 2.6.3, sector entry count is a rough representation of the actual demand that is practically dealt with by ATCOs. This is because, it accounts for neither the specific complexity nor the distribution of air traffic over the period of interest. For instance, if a sector entry count of 40 aircraft per hour is counted, the same number is considered as the expected demand for the whole hour, regardless of whether 20 aircraft enter the sector in the first ten minutes or there is an even distribution of 40 aircraft throughout the hour. Therefore, the entry count value does not provide an accurate estimation of the expected ATCO workload. Recent researches have considered an additional criterion “the sector occupancy count (See Section 3.1.4)” [91][13]. However, the particular characteristics of the expected traffic still lacks in this criterion.

This thesis diverts from the above conventional criteria. The determination of the expected traffic demand should include the analysis of traffic complexity, particularly considering the expected aircraft conflicts that greatly affect ATC workload and airspace capacity. This thesis suggests that the trigger to activate an ATFCM DCB regulation should be the number of the identified expected aircraft conflicts exceeding a pre-defined conflict threshold count, established at pre-flight phase.

The aircraft trajectory compatibility conditions could be established considering a trade-off between the overall airspace capacity and the desired probability of ATCOs' tactical interventions determined by the probability of aircraft conflicts. The high levels of uncertainties in the trajectory definition at pre-flight phase must be considered in order to estimate the aircraft trajectory compatibility condition as discussed further in Chapter 5.

If expected conflicts are identified and measures for aircraft trajectory de-confliction are applied at pre-flight phase, it is reasonable to believe that the amount of actual conflicts requiring tactical ATC intervention will be reduced. The operational traffic demand could then be determined from the analysis of aircraft trajectories' spatiotemporal interdependencies rather than aircraft counts. This approach is an integral part of the ATFCM DCB method proposed in this thesis, and is in line with the Trajectory Based Operations (TBO) concept as discussed in Section 2.7.

2.7 Towards an ATFCM DCB Based on TBO

2.7.1 SESAR and NEXTGEN ATM Paradigm Shift

As briefly discussed in Section 1.2.2, in order to mitigate the current ATM limitations and better face future challenges, new initiatives are underway in different parts of the world with an aim to reform the current ATM system. In Europe in particular, the Single European Sky (SES) initiative was launched by the European Commission (EC) in 1999 to coordinate all previously local disjointed and new European ATM research and development efforts [92]. The SES aims to meet future ATM needs through legislation at European level rather than local levels. It has the following three key objectives [92]:

1. Restructure the European airspace according to traffic flows rather than national borders;
2. Create additional ATM system's capacity;
3. Increase the overall efficiency of the ATM system.

The SES is supported by SESAR, which plays the role of being SES's operational and technical pillar [24]. Similarly, USA is running the NextGen programme [16]. Both programmes seek to help in creating an ATM paradigm shift with the support of new and innovative technologies.

Focusing on SESAR, its main objectives are to investigate on how the forecasted air traffic growth in Europe can be accommodated, how European airspace can be optimised, how aircraft delays can be reduced and ways to improve the safety of the European ATM system [24]. To achieve these objectives, the ATM requires several coordinated operational changes which have been defined in the SESAR master plan. **Figure 18** shows the current underway and short term ATM operational changes in Europe.

As shown in **Figure 18**, these changes are classified according to different operating environments; airport, Terminal Manoeuvring Area (TMA) and en-route in which they are expected to provide performance benefits for the overall ATM network. In addition, these changes are classified based on whether they are considered as "Pilot Common Project (PCP)¹³ essential operational changes" defined as ATM changes that are included in the PCP, "new essential operational changes" defined as ATM changes beyond the PCP plus additional operational changes related to safety and "operational changes" defined as ATM changes considered today as non essential [24].

An essential operational change whether considered under PCP or new, is defined as *"an ATM operational change that provides significant network performance improvements to the ATM operational stakeholders"* [24].

¹³ PCP is the first European common project which aims to deploy in a timely, coordinated and synchronised way, the first set of ATM functionalities that are mature for implementation as per the Regulation (EU) 716/2014 and that contribute to the essential operational changes identified in the European ATM Master Plan 2012.

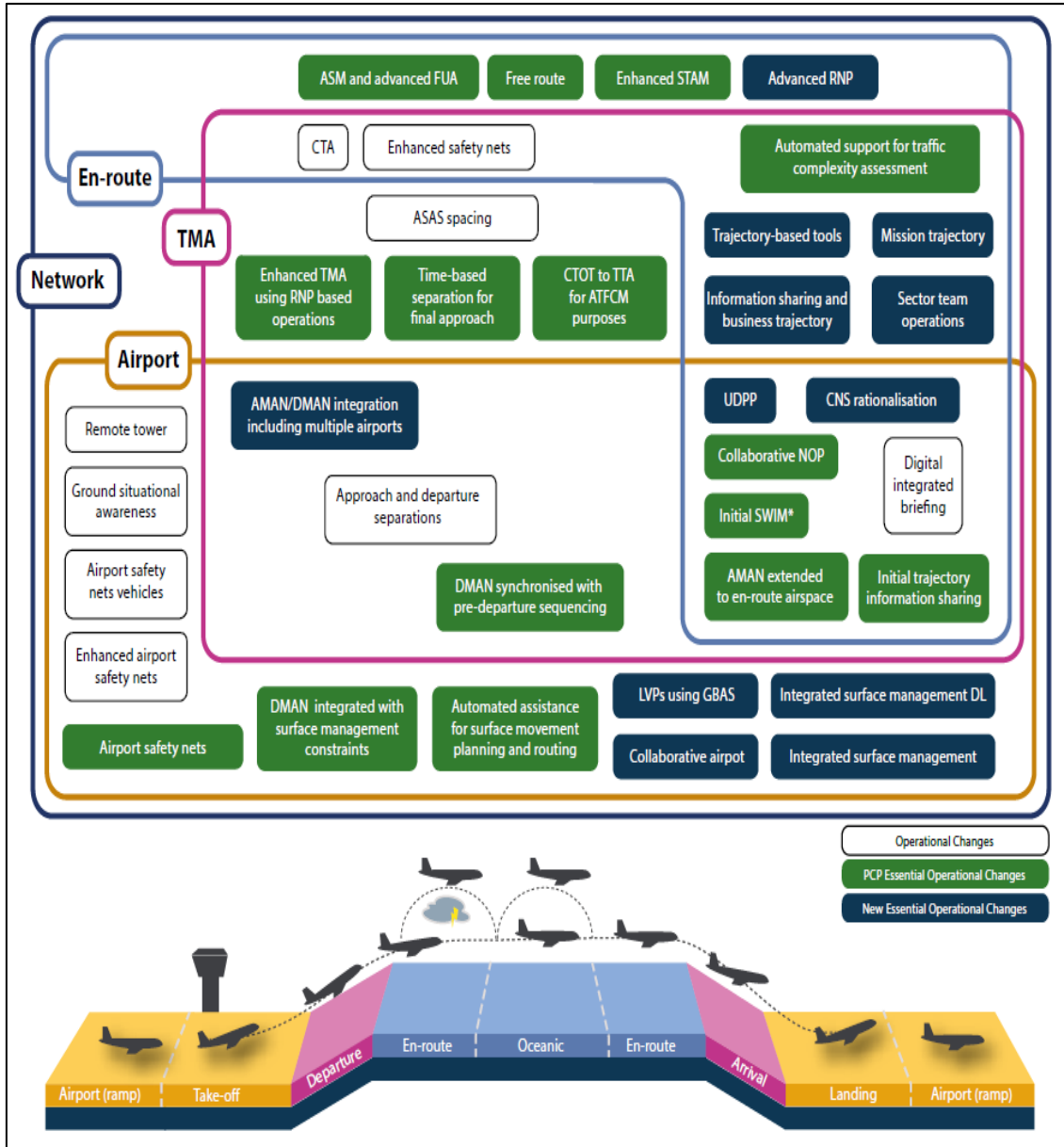


Figure 18: SESAR operating environments [24]

Through the above operational changes, SESAR aims to achieve several performance ambitions by year 2035. As shown in **Table 2**, these ambitions have been defined using as a baseline reference, the ATM performance values observed in different ATM Key Performance Areas (KPA) in 2012 [24]. These ambitions have been designed to contribute towards achieving SES high-level goals of which they are defined in alignment with, as shown in **Table 2**. These precise goals are defined quantitatively as follows:

1. 10-fold improvement in safety;
2. 10 % reduction in aviation foot print;
3. 50 % ATM costs reduction per flight;
4. 3-fold increase in ATM capacity.

Key performance area	SES High-Level Goals vs. 2005	Key performance indicator	SESAR ambition vs. baseline 2012	
			Absolute saving	Relative saving
 Cost efficiency: ANS productivity	Reduce ATM services unit cost by 50% or more	<ul style="list-style-type: none"> • Gate-to-gate direct ANS cost per flight <ul style="list-style-type: none"> - Determined unit cost for en-route ANS* - Determined unit cost for terminal ANS* 	EUR 290-380	30-40%
 Operational efficiency	-	<ul style="list-style-type: none"> • Fuel burn per flight (tonne/flight) • Flight time per flight (min/flight) 	0.25 -0.5 tonne 4-8 min	5-10% 3-6%
 Capacity	Enable 3-fold increase in ATM capacity	<ul style="list-style-type: none"> • Departure delay (min/dep) <ul style="list-style-type: none"> - En-route air traffic flow management delay* - Primary and reactionary delays all causes • Additional flights at congested airports (million) • Networkthroughput additional flights (million) 	1-3 min 0.2-0.4 (million) 7.6-9.5 (million) <small>Additional flights, not saving</small>	10-30% 5-10% ¹ 80-100% ²
 Environment	Enable 10 % reduction in the effects flights have on the environment	<ul style="list-style-type: none"> • CO₂ emissions (tonne/flight) <ul style="list-style-type: none"> - Horizontal flight efficiency (actual trajectory)* - Vertical efficiency - Taxi-out phase 	0.79 -1.6 tonne	5-10%
 Safety	Improve safety by factor 10	<ul style="list-style-type: none"> • Accidents with ATM contribution 	No increase in accidents	Improvement by a factor 3-4
 Security	-	<ul style="list-style-type: none"> • ATM related security incidents resulting in traffic disruptions 	No increase in incidents	

* Targeted by the Performance Scheme

1. Additional flights that can be accommodated at congested airports, representing 5-10% of flights at congested airports (~31% of 14,4 (million) flights in 2035).

2. Additional traffic accommodated in 2035 in comparison with 2012 and associated with ANSP productivity gains, enabled by SESAR. Note: Numbers are rounded.

Source: Eurocontrol PRB, SES, EC ACE report (2012), Master Plan Campaign Expert Workshops.

Table 2: SESAR ATM performance ambitions for 2035 [24]

To achieve the above SESAR ambitions and eventually achieve SES high-level performance targets, SESAR have recognised that the current ATM concept of operations must be changed from a fundamental level. Hence, SESAR have defined a new ATM paradigm shift, which embodies the following main parading shifts [2]:

1. Shift from airspace based operations to TBO concept;
2. Shift from tactical management towards a more proactive system;
3. Shift from a controller based system towards a more distributed system.

2.7.2 The TBO Concept and its Expected ATFCM DCB Benefits

A key common pillar of SESAR [11], NextGen [16] and of other ATM paradigm shift initiatives such as the Collaborative Actions for Renovation of Air Traffic Systems (CARATS) in Japan [93], is the parading shift from the current airspace based operations to the new TBO concept. TBO is based upon the 4D trajectory concept [94].

As discussed in Section 2.6, currently, aircraft FPLs are typically submitted to the NM at least a few hours before the planned aircraft's ETOT. This implies that most of the AUs' and NM's DCB decisions are taken far before the flight is in the air, reducing the predictability and efficiency of all ATM stakeholders and limiting network performance. The TBO concept addresses this issue by proposing a new management of ATM operations based on the aircraft 4D trajectories, which will enable to execute each flight as close as possible to AU's intentions [66]. TBO defines an iterative refinement process of aircraft 4D trajectory until the aircraft departs. It defines how far in advance of aircraft's ETOT this 4D trajectory refinement process will start, the Collaborative Decision Making¹⁴ (CDM) process required and the type of information required to

¹⁴ According to ICAO (DOC 9971), Collaborative decision-making (CDM) is defined as a process focused on how to decide on a course of action articulated between two or more community members. Through this process, ATM community members share information related to that decision, agree on, and apply the decision-making approach and principles. The overall objective of the process is to improve the performance of the ATM system as a whole while balancing the needs of individual ATM community members.

solve DCB problems and improve system's predictability while preserving as much as possible, the AUs' desired FPLs.

A 4D trajectory is an aircraft's flight path defined with a required accuracy associated to all three spatial coordinates (latitude, longitude and altitude) plus time (target times or time constraints at designated waypoints) as illustrated in **Figure 19** [66]. Therefore, a 4D trajectory in itself refers to the integration of time into the conventional 3D aircraft's trajectory. It aims to ensure as much as possible, a practically unrestricted and optimum trajectory for AUs in an exchange that in nominal situations, AUs will meet accurately the agreed aircraft's arrival time constraints at designated waypoints to improve the ATM efficiency.

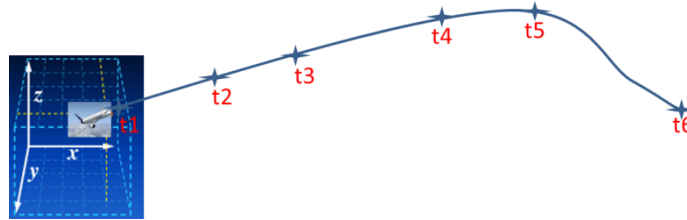


Figure 19:4D Trajectories defined in three spatial coordinates plus time

The 4D trajectory will be agreed before the flight, and the AUs will commit to fly the aircraft within the required accuracy along the agreed trajectory [66], while the ANSPs and airports facilitates the execution of that trajectory. The resulting increased accuracy of flight planning and execution is expected to result into several specific benefits including [66]:

1. Enabling strategic de-confliction and hence, easier to handle traffic for ATCOs;
2. Increased capacity as ATCOs will be able to handle safely more traffic;
3. Increased overall predictability and efficiency of the traffic network;
4. Optimal operations for AUs as aircraft will fly their preferred trajectories;
5. Better service provided due to increased interoperability between involved stakeholders, enabling fewer trajectory distortions and hence, reduced AUs' operating costs.

This thesis focuses on the first of the above benefits “strategic de-confliction” which is seen as a major enabler for the rest of the above expected TBO benefits. As discussed in Section 1.4, for strategic de-confliction to be effective and enable other TBO benefits, it should result in a reduction of the number of conflicts at tactical level, thus, reducing the air traffic complexity and ATCOs tactical interventions. Indeed, as highlighted in Section 1.4, for en-route operations, SESAR explicitly articulates that “*the main goal of SESAR’s new ATM concept is to deploy tools to manage complex situations in order to reduce ATC workload by strategic de-confliction measures*” [11]. By proposing a pre-flight de-confliction method at ATFCM DCB level, this thesis is then in line with the above goal. The envisioned pre-flight de-confliction will be enabled by the layered planning approach of the trajectory as discussed in Section 2.7.3.

2.7.3 The Layered Planning Lifecycle of the Trajectory

The envisioned pre-flight de-confliction under TBO, will be enabled by a layered planning approach defined by the Business Trajectory (BT) concept. The BT’s lifecycle is illustrated in **Figure 20**, where it is shown that the design of aircraft’s trajectory starts in the long term phase, possibly years before the flight execution under the form of Business Development Trajectory (BDT). The BDT is a trajectory that is internal to AU (analogous to the current FOC’s aircraft internal schedule) and not shared outside the AU’s organisation [11].

Once the BDT has reached a certain level of stability, it is made available to the rest of ATM community and becomes the Shared Business Trajectory (SBT). The SBT is the trajectory through which potential discrepancies with the expected network constraints might already be detected by the NM, and AUs notified of any constraints from which their SBTs should be refined to [11]. This is an iterative process that should ideally end once an AU’s preferred and feasible trajectory has been agreed among all involved ATM stakeholders, or otherwise, in time-critical situations imposed by the NM. The above negotiation process will rely on the CDM mechanisms [11], designed to solve mismatches between the air traffic demand and system’s capacity.

In a time horizon of few hours to a few minutes, the agreed SBT becomes the Reference Business Trajectory (RBT) [11]. An RBT is the trajectory that the AU agrees to fly and the ANSPs and airports agree to facilitate; it represents the most optimal trajectory for all ATM stakeholders, since it is defined considering as much as possible both the network constraints and AU's internal business preferences. The RBT is then, the objective to be achieved by a particular flight but it is progressively authorised during flight execution. However, under TBO, the modification of the RBTs by ATC tactical interventions should be considered as an exception [11].

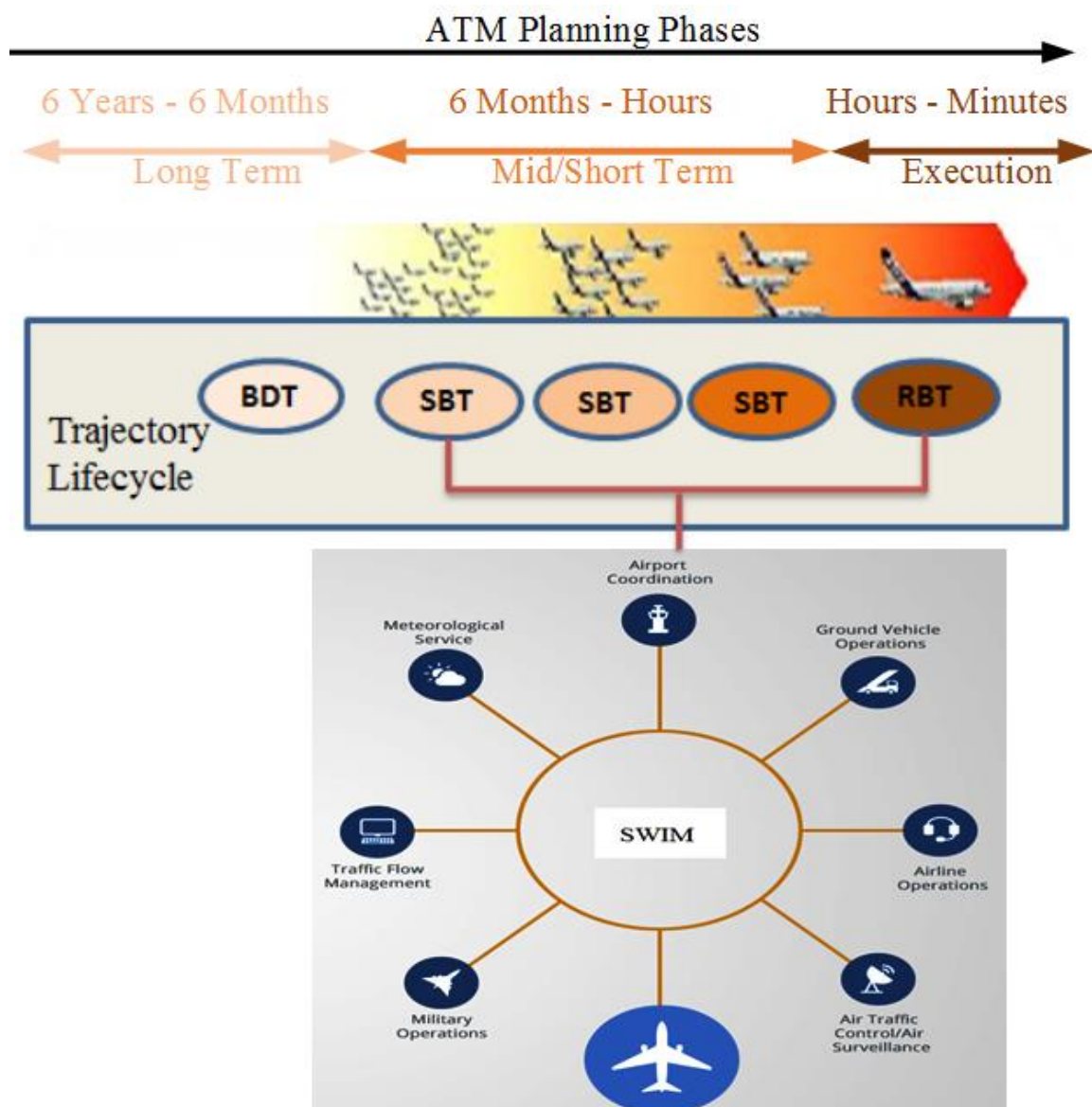


Figure 20: Collaborative layered trajectory planning under BT concept [11]

The above discussed layered planning process of the aircraft trajectory under TBO, presents new opportunities to deal with the DCB problem. This process will be supported by better information exchange and a more distributed network centric system enabled by the System Wide Information Management (SWIM) platform as illustrated in **Figure 20** [95]. Through SWIM platform, whenever ATM constraints needs to be applied, all ATM stakeholders will share these constraints in order to collaboratively define flyable, optimal and AUs' preferred RBTs.

This thesis suggests that the above process shall include measures to detect downstream trajectory interdependencies within each set of SBTs for the whole ECAC network, and the aforementioned constraints shall be intended to relax those interdependencies in order to define conflict free RBTs at pre-flight Short Term ATFCM (STAM)¹⁵ level. This will enable to provide at tactical level, scenarios of conflict free RBTs. Hence, reducing the ATC tactical interventions, as well as helping to refocus the ATFCM from its current DCB solutions focused on local performance to DCB solutions focused on global network level performance.

In addition, as briefly discussed in Section 2.6.3 and Section 2.6.4, from AUs perspective, some flexibility is required in the trajectory management process for continuous flight optimisation in an environment that contains unpredictability. From ATFCM perspective, a certain level of predictability of flight behaviour is needed to ensure the required performance of the ATFCM functions to support those flights. Therefore, there is a need for a balance between the actual need of the ATFCM system and the needs of individual AUs to enable adherence to an agreed trajectory. This adherence, requires pre-flight trajectory complete de-confliction, as part of the negotiation to produce RBTs from SBTs as proposed in this thesis. Furthermore, new advancement in CNS and Avionics (CNS+A) technologies will enable increased flexibility in the flight planning process as well as increased aircraft adherence to the planned trajectory as discussed in Section 2.7.4.

¹⁵ STAM is an approach to smooth sector workloads by reducing traffic peaks through short-term application of minor ground delays, appropriate flight level capping and exiguous rerouting to a limited number of flights.

2.7.4 The Target ATM Technological Enablers

The employment of several CNS+A capabilities has been identified by SESAR as necessary technological enablers of the ATM Paradigm shift; these mainly include:

Communication Technological Enablers: The ATM paradigm shift will mainly rely upon digital communication enabled by the use of technologies such as the Controller Pilot Data Link Communication (CPDLC), VHF Digital Link (VDL) mode and 4D Trajectory Datalink (4D-TRAD) among others [96]. It has been identified by SESAR that the use of datalink is a main requirement to achieve full integration of ground and airborne ATM communication systems. Datalink is also a pre-requisite to enable digital data exchanges between all ATM stakeholders such as the data information required to support the SWIM platform [95].

The SWIM platform is envisaged as a future ATM net-centric intranet, which will provide a complete change in the archetype of managing information across the whole European ATM system. It will provide a common platform for all ATM stakeholders with the right permission and adequate datalink installations to access the European ATM shared information [95]. **Figure 21** illustrates the architecture of how the current ATM information is shared (see **Figure 21** left picture) and how it will be shared with the use of SWIM (see **Figure 21** right picture). In the current situation, the ATM information exchange is achieved through point-to-point connections between individual ATM stakeholders. This manner of information sharing cannot enable a seamless, reliable and efficient exchange of ATM information for a timely CDM process required to support a TBO based DCB process. On the contrast, SWIM will provide a one data source for integrated flight planning to enable a timely CDM among all ATM stakeholders. According to EUROCONTROL [97], “*the implementation of SWIM will aim at structuring, harmonizing and standardizing the process of collaborative information exchange throughout the entire ATM system by using an integrated, net-centric and IP-based infrastructure*”. All ATM stakeholders will represent the nodes of the SWIM network infrastructure.

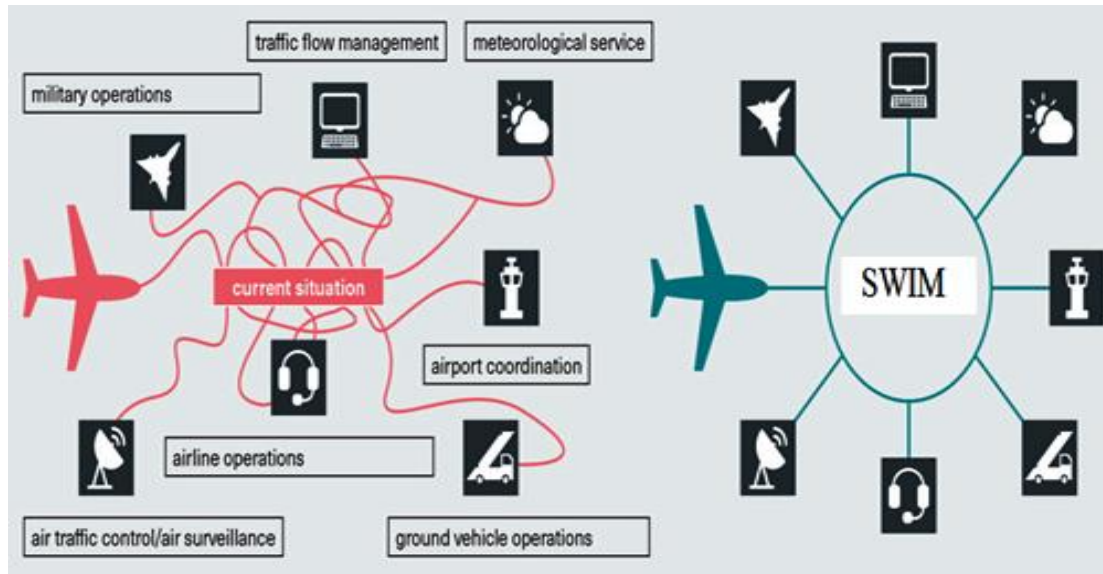


Figure 21: ATM information sharing without SWIM (left picture) and with SWIM (Right picture) [97]

SWIM benefits will include improved shared situational awareness among all ATM stakeholders, and coordination of planned 4D trajectories to achieve a holistically efficient use of the airspace. The scope of SWIM data will cover all relevant information such as 4D trajectories, surveillance data, aeronautical information and meteorological data required for efficient ATM operations. SWIM is thus, fundamental for TBO based ATFCM DCB. Efficient DCB is only possible if timely trajectory information is available to all affected ATM stakeholders. Consequently, the availability of SWIM for information sharing is assumed in this thesis.

Navigation Technological Enablers: Future ATM operations will take advantage of the recent advancements in navigation technologies such as the GNSS that supports RNAV and the Required Navigation Performance (RNP) procedures, which are key enablers of the ICAO Performance Based Navigation (PBN) concept [25].

As described by ICAO [25], and as illustrated in **Figure 22**, PBN is consisted of three components: Navigation application, NAVAID infrastructure and navigation specification. The “navigation application” component refers to the implementation of a navigation specification and its supporting NAVAID infrastructure applied in the

context of an airspace concept to ATS routes, procedures, and/or a defined airspace volume. The “NAVAID infrastructure” component refers to the NAVAIDS necessary for each navigation specification. As shown in **Figure 22**, the “PBN navigation specification” component is what is consisted of the RNAV and RNP specifications.

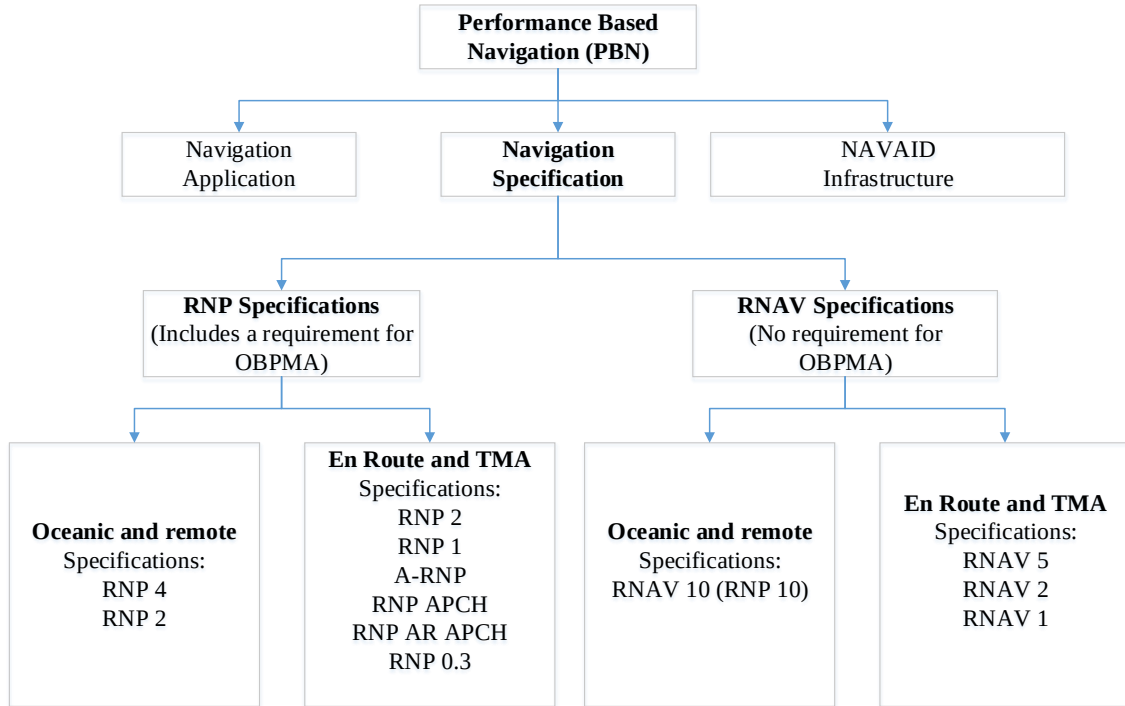


Figure 22: PBN Specifications (RNAV and RNP)[25]

RNAV is defined as a method of navigation, which permits aircraft to fly any desired flight path defined by waypoints such as geographic fixes that are not necessarily based on ground NAVAIDS. The condition for RNAV is that aircraft operates within the coverage of the station-referenced NAVAIDS, and or within the limits of the capability of self-contained aids for the duration of the flight [25]. The main advantage of RNAV specification is the removal of some current constraints imposed by the fixed ground based NAVAIDS (e.g. VHF Omnidirectional Range (VOR)/ Non-Directional Beacon (NDB)) on the aircraft navigation capability. **Figure 23** illustrates this advantage, where the blue line shows an aircraft’s RNAV route without constraints of the ground based NAVAIDS vs. the grey line showing aircraft’s route without RNAV capabilities [25].

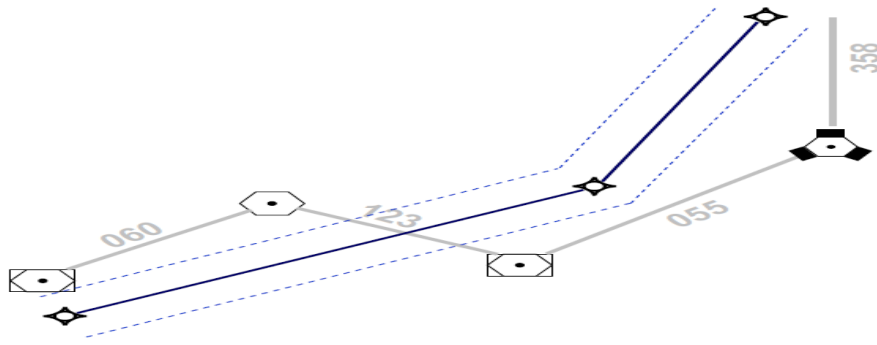


Figure 23: Illustration of RNAV route

As shown in **Figure 22**, RNP simply refers to RNAV plus On Board Performance Monitoring and Alerting (OBPMA) requirement. The RNP definition can be succinctly stated as the navigation performance necessary for aircraft operation within a defined airspace, meeting specific requirements defined in terms of four elements namely; accuracy, integrity, continuity and availability. A detailed description of these elements is provided in [25]. Among these elements, the accuracy element specifies that an aircraft operating in a particular required RNP value airspace shall have a maximum Total System Error (TSE) (see **Figure 24**) that is less than that RNP value for 95% of its flight time. In other words, the maximum TSE with 95% probability shall be equal or less than $1 \times \text{RNP}$ value.

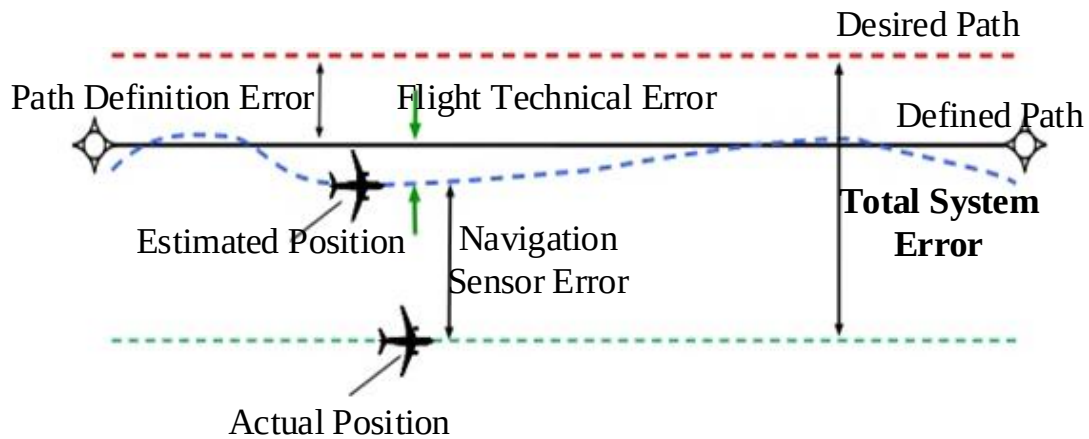


Figure 24: Definition of navigation total system error

Figure 25 shows the definition of RNP accuracy limit and containment limit, where it is shown that $\pm 2 \times \text{RNP} \times X = \text{corridor length of the containment limit (in NM)}$ or ± 2 corridor length of the accuracy limit (in NM). As discussed later in Chapter 5, RNP 1

capability that requires lateral TSE of ± 1.0 NM accuracy for 95% of flight time is assumed in this thesis, considering that it is sufficient to support the required predictability of en-route flights in the considered TBO environment.

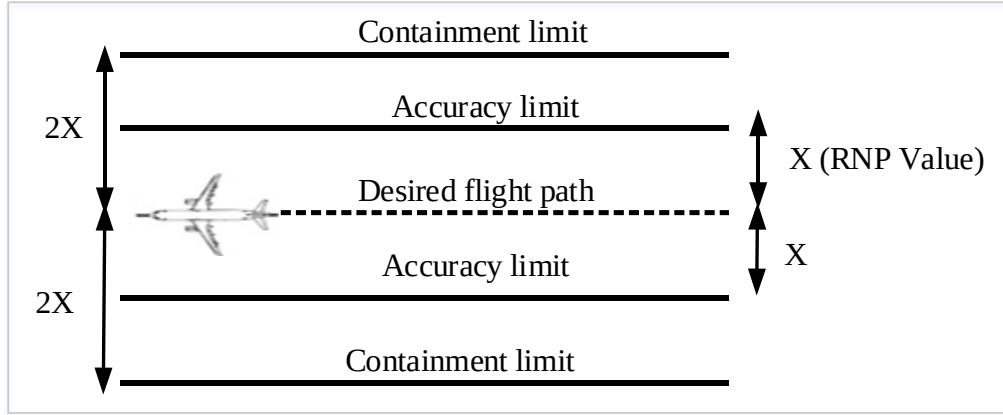


Figure 25: Definition of RNP accuracy and containment limits

The advancements in navigation technologies, is key to enabling the Free Routing (FR) concept. This concept corresponds to the ability for AUs to define a FPL with at least a significant part of the intended route not defined according to published route segments, but specified by the AUs themselves [98]. Hence, the aircraft's route under FR concept is a user-preferred route. However, such a route is not necessarily a direct route, but the flight is expected to be executed along the direct route between any two consecutive waypoints specified by the AUs [98]. FR operations concern flights in cruise or vertically evolving within FRA, and could only be performed within this airspace. Therefore, FRA is a specified airspace within which AUs may freely plan a route between a defined entry point and a defined exit point with the possibility to route via intermediate waypoints without reference to the conventional ATS route network, subject to airspace availability [27].

The performance of the DCB method proposed in this thesis is analysed considering its implications in both flight operations in the conventional ATS route network and flight operations in FRA.

Another key navigational enabler of the ATM paradigm shift is the Advanced Flight Management System (AFMS) [94][99], which is an avionic automation system on-board aircraft that enables it to follow a vertical and lateral profile with optional specified speeds for each segment of that profile. Key to TBO concept is the Controlled Time of Arrival (CTA) capability, achieved by the AFMS's Required Time of Arrival (RTA) functionality [99]. The RTA enables aircraft to adjust the speed in order to arrive at a given 3D waypoint at or within a tolerance of a defined target time. The CTA can be defined as an ATM imposed time constraint on a defined waypoint, to be achieved by the aircraft within a required accuracy.

This thesis assumes that all aircraft are equipped with the AFMS with a CTA capability, mainly due to the following two main reasons:

1. To minimise the along-track deviations in the time of arrival at en-route conflicted junctions (see Section 5.3.4)
2. To enable aircraft to adhere to the required adjustments in Time of Arrival (TOA) at en-route junctions for conflict removal.

Surveillance Technological Enablers: The advanced surveillance technologies are required to provide more precise air traffic monitoring and enhanced awareness of air traffic situation, that go beyond the capabilities of the current Secondary Surveillance Radar (SSR) and Primary Surveillance Radar (PSR) systems [100]. Therefore, it is envisaged that future ATM operations will be enabled by a combination of new surveillance technologies including the Automatic Dependent Surveillance (ADS) technologies as well as the Wide-Area Multilateration (WAM) system [96]. For a comprehensive description of these technologies and their expected benefits, the reader is referred to [100][101]. Considering ADS technologies in particular, such as the ADS-Broadcast (ADS-B), its accuracy is equivalent to that of satellite navigation system such as the Global Navigation System (GPS), which is much higher than that of radar-based systems [101]. In addition, the accuracy of ADS-B is uniform over larger areas, while that of radar-based systems decreases with the increase in distance away from the radar head [101].

3 REVIEW OF ATFCM-DCB OPTIMISATION PROBLEMS AND TAXONOMY OF TOOLS

The Air Traffic Flow and Capacity Management (ATFCM) optimisation problems have been addressed intensively over the years. The existing models were developed to adapt and fit the demand to the capacity. These models can be classified into two main modeling approaches:

1. Macroscopic approaches;
2. Microscopic approaches.

3.1 Macroscopic ATFCM-DCB Modelling Approaches

Currently, macroscopic ATFCM approaches are usually applied to wide geographical areas, providing corrective measures before the aircraft is flying. They use aggregated Flight Plans (FPLs) as the input, and the Air Traffic Control (ATC) sectors' and airports' capacities as the “limiting factor”. Throughout a Demand and Capacity Balancing (DCB) dynamic exercise, the initial FPLs can either be directly approved or “regulated”. The regulation action then becomes the available “control action” and usually involves ground delay or re-routing as discussed in Section 2.6.2. The ground delay is the most common regulation criteria and the associated ATFCM problem is called the “Ground Delay Problem (GDP)”, which seeks to minimise the sum of airborne and ground delay costs when demand exceeds the allowed capacity. The GDP problem has been studied in a simple airport capacity constrained scenario [102][103], and in a more complex scenario involving capacities of a network of interconnected airports and connecting flights whilst considering cascading effect of delays on flights in the network [104]. The former is commonly known as the “Single Airport Ground Holding Problem (SAGHP)” where the latter is known as the “Multi-Airport Ground Holding Problem (MAGHP)”.

Macroscopic approaches have also been applied to solve the ATFCM DCB problem, commonly known as the “Generalized Air Traffic Flow Management Problem (GATFMP)” which considers the full network capacity constraints (airports' and en-route sectors' capacity constraints), without the possibility of re-routing [105]. This

problem has also been extended in the literature to include the possibility of re-routing, which is known as the “Air Traffic Flow Management Re-routing Problem (ATFMRP)” [106].

This section provides a review of the above ATFCM problems including a brief description of their context and scope, followed by a review of the principal approaches that have been applied to solve each of them. A critical analysis is then provided in light of the current ATFCM DCB challenges.

3.1.1 The Single Airport Ground Holding Problem (SAGHP)

The first optimal approaches to the SAGHP problem were developed by Andreatta and Romanin-Jacur [103]. They addressed a static probabilistic SAGHP by considering a greatly simplified model, but this model is believed to contain major fundamental conceptual aspects which all other existing SAGHP models are based on [104]. This model considers a single arrival airport capacity scenario, which assumes that congestion may only occur at the arrival airport and only during a given single time period of interest. The model is neither multi-period nor dynamic, but it explicitly accounts for the probabilistic nature of the arrival airport’s capacity by treating capacity as a random variable in that single period of interest. As the arrival airport is the only capacitated element of the network, it is considered the only possible source of delays. A dynamic programming algorithm was used to determine optimal ground delay assignments, allocated to each aircraft in terms of aircraft release time at the departure airport to minimise the total delay cost (ground delay + airborne delay at the destination airport).

Terrab and Odoni [107], re-formulated the above SAGHP model to address multiple capacity scenarios at the arrival airport. For each capacity scenario, they considered the arrival capacity as a deterministic function of time over a given time period of interest, as illustrated in **Figure 26**. Each arrival capacity scenario (scenario x) has an associated probability (Probability (scenario x)) of materializing where the objective function is weighted over all the possible arrival capacities. The problem was solved by a Dynamic Programming (DP) algorithm, of which time complexity significantly increased with the

number of arrival capacity scenarios considered. Consequently, it was concluded that the model had major scalability problems and required enormous and unrealistic computational effort to be solved.

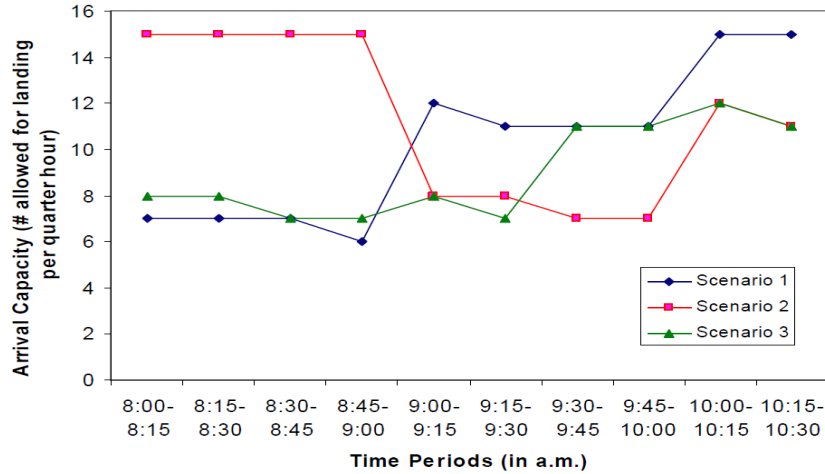


Figure 26: Arrival airport capacity as a deterministic function of time for SAGHP [107]

The multi-capacity scenario SAGHP was eventually optimally solved with reasonable computational effort by Richetta and Odoni [108]. The difference with the previous approach developed by Terrab and Odoni is that, instead of trying to find optimal solution for each aircraft, the authors developed a model that simplifies the structure of the control mechanism by finding optimal solutions for groups of aircraft. Aircraft were grouped according to their delay cost class and by their schedule such that the aircraft within the same ground delay cost class and scheduled to arrive at the destination airport in the same time period of interest, would belong to the same group. Weather information updates over time were used to model different alternative capacity scenarios of the arrival airport.

To obtain faster numerical solutions, it was assumed that the number of arrival alternative airport's capacity scenarios within a day resulting from weather information updates is a finite small number. A probability tree was used to model the dynamic evolution of the capacity scenarios and their associated probabilities. For instance, **Figure 27** shows a situation where weather forecast updates resulted into three alternative capacity scenarios ($x = 3$) for arrival airport Z. The forecast was updated

three times during the time interval $[0, B]$, where three decision time stamps (t_1, t_2 and t_3) define three stage time intervals at which weather forecast is updated and decisions are made, resulting into three distinct constant airport arrival capacity scenarios over time intervals $[t_1, t_2)$, $[t_2, t_3)$, and $[t_3, B]$. This implies that X capacity scenarios require at most X decision stage time stamps. The objective is to allocate and or revise aircraft ground delays at the beginning of each decision stage. An optimal solution was obtained considering both static and dynamic cases. For a static solution, the time interval $[t_1, B]$ comprised a single stage, resulting in a "here-and-now" optimal solution, which only allocates ground delay to aircraft at time stamp t_1 . In the dynamic case, ground delay decisions can be made progressively at time stamps t_1, t_2 and t_3 .

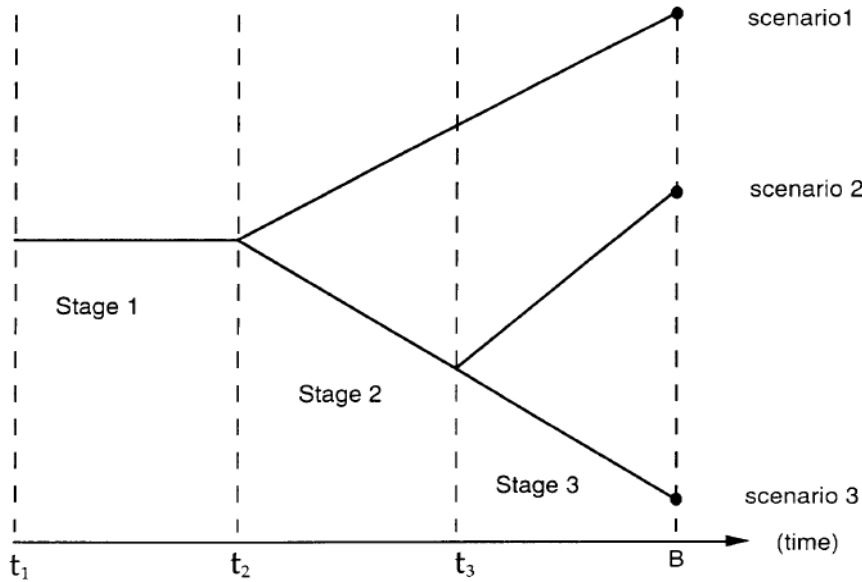


Figure 27: Arrival airport capacity probabilistic scenarios for SAGHP [108]

In both static and dynamic cases, Richetta and Odoni claimed optimal results even when the model was applied to busiest airports in the United States. In fact, this model is currently widely considered as the most complete SAGHP model [108]. However, like all other SAGHP models, since this model only considers a single arrival airport, it fails to consider the effects of the ground delays on the entire network of airports. Consequently, after this model was developed, the subsequent researchers in the literature shifted the focus towards solving the “MAGHP”.

3.1.2 The Multi Airport Ground Holding Problem (MAGHP)

The MAGHP models attempt to find optimal aircraft ground delay allocations by considering scenarios involving a network of airports where in most cases, only the arrival airports' capacity remains the only constrained element of the network , and in a few other cases, both the arrival and departure airport capacities are constrained [109] . Several MAGHP models have also considered the interdependencies between the airport arrival and departure capacities as well as the cascading effects on connecting flights and the effects of flight cancellations [109].

Clearly, there is significant increase in the scope of the ATFCM DCB problems considered in MAGHP approach as compared to SAGHP approach. Nevertheless, research efforts on the former were short-lived. This was mainly due to the increased awareness that, without the consideration of the en-route sectors' capacity constraints, ATFCM DCB modelling approaches based on ground delay allocation alone were operationally futile. This awareness can be attributed to the increase in traffic growth and high traffic densities in the US and European en-route sectors that could have started to be more apparent at that time. Consequently, there are essentially only four main MAGHP optimisation models. A comprehensive description of these models can be found respectively in [109], [110], [111] and [112] .

The rationale behind the above four main MAGHP models is essentially the same; they have a common objective of minimising the total delay costs (ground delay costs + airborne delay costs), subject to airport capacity constraints (arrival capacity or arrival and departure capacity) and aircraft connectivity constraints. The models only differ in the definition of the optimisation decision variables. Therefore, their difference is technical rather than substantive.

A comparative analysis of these models is provided in [110], where it is concluded that the model developed in [111], has superior computational performance over the other three models. In addition, this is the only MAGHP model that includes constraints capturing the existing interdependence between airport arrival and departure capacities. These interdependence constraints enable the solution determining the optimal

distribution of the airport's capacity between the arrivals and departures, in addition to the aircraft delay assignment objective.

It is necessary to highlight that the major limitation of all the aforementioned SAGHP and MAGHP approaches and their other variations in relation to the present ATFCM DCB challenges, is their assumption that the capacity of airspace (ATC Sector(s)) is unconstrained. Therefore, no other DCB control techniques such as re-routing and speed control are considered as control variables. In today's congested airspace such as that over Europe, this assumption is too idealistic.

3.1.3 The Generalized Air Traffic Flow Management Problem (GATFMP)

The GATFMP is an ATFCM problem that removes the above unrealistic airspace capacity assumption by considering the full network capacity constraints (airports' and en-route sectors' capacity constraints). In order to minimise the total aircraft delays, several GATFMP models solve the problem by tactically assigning some airborne delays to aircraft through the airborne holding at specific en-route points, in addition to ground delays at departure airport [113]. On the other hand, other GATFMP models solve the problem by finding the optimal departure and sector occupancy time for each aircraft in the network that minimises the total network delay [114].

A common characteristic of the current GATFMP optimisation models is that they are all deterministic and all assume that the available capacity of each element (each airport and each sector) and the traffic demand are known in advance [115]. In addition, they commonly conclude that the problem is NP-hard [115]. However, Tosic et al. [116] and Delahaye and Odoni [116], have suggested heuristics that proved to be computationally efficient. Moreover, the EUROCONTROL CASA algorithm (see Section 2.6.2) is essentially a heuristic algorithm for solving the GATFMP. The CASA algorithm is indisputably computationally efficient, typically providing solutions within 30 seconds that would otherwise be considered too large for optimisation models. However, as discussed in Section 2.6.2, CASA is not short of limitations in relation to the present ATFCM DCB challenges, and there is a considerable room for improvement in this respect.

Moreover, just like MAGHP and SAGHP models, the current GATFMP models also do not allow for other techniques such as re-routing and speed changes as ATFCM DCB control variables.

3.1.4 The Air Traffic Flow Management Re-routing Problem (ATFMRP)

The ATFMRP is considered the most complete of the existing macroscopic ATFCM DCB problems. It includes aircraft re-routing as a control action in addition to the ground delay.

In all variations of the ATFMRP modelling approaches, the airspace topology is modelled as a network of sector volumes with one or multiple entry and exit points at which aircraft fly into and out of each sector [117]. The airports are represented as the nodes of the network. Airports and sectors are interconnected by flight routes such that each aircraft may enter a particular sector either from an airport or from an adjacent sector as illustrated in **Figure 28**.

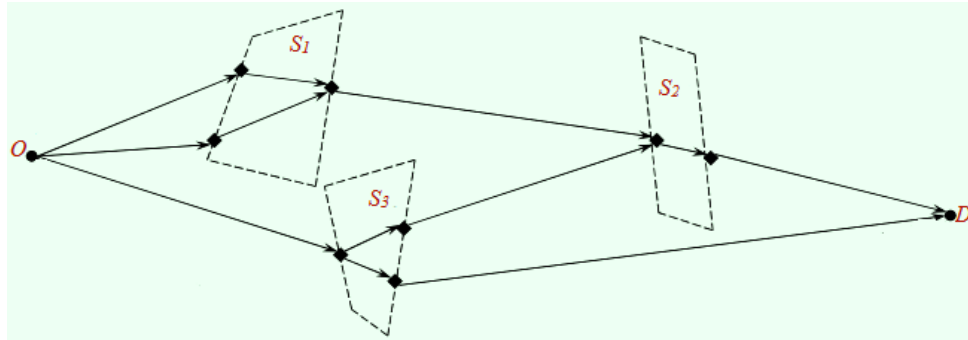


Figure 28: Airspace topology for ATFMRP modelling [117]

The network topology used in these models, enables to place a capacity limit on each sector based on the traffic demand, computed based on the number of aircraft entering and leaving each sector S_i through its entry and exit point(s) for a given time period t [117][106][118]. This network topology contains several network links representing alternative routes that an aircraft may fly to enable it passing through other sector(s) in a case of capacity constraints that may make the originally planned sector (s) unavailable. Therefore, allowing for the possibility of re-routing. For instance, from **Figure 28**, the network consists of three sectors (S_1 , S_2 and S_3) with several network links representing

alternative routes that an aircraft may use. For aircraft f to fly from its origin airport O to its destination airport D , they may transit either through sectors: S_1, S_2 or through S_3, S_2 or just through S_3 , using one of the sector(s)' various entry and exit points. Then for any time period t , the traffic flow demand computed in terms of the number of aircraft simultaneously in any sector S can be formulated as:

$$N_{s,t} = N_{s,t-1} + \sum_{f \in F} \sum_{i \in I_s^f} (x_{i,t}^f - x_{i,t-1}^f) - \sum_{f \in F} \sum_{j \in J_s^f} (x_{j,t}^f - x_{j,t-1}^f) \quad (3-1)$$

From Equation (3-1), it can be seen that for any sector S during the time interval t , the number of aircraft in that sector $N_{s,t}$, is equivalent to the number of aircraft previously in that sector $N_{s,t-1}$ plus the number of aircraft entering and leaving that sector at each entry point $i \in I$ and each exit point $j \in J$. The decision variable x will be $x = 1$ if aircraft f arrives at any capacity constrained element (sector entry/exit point or airport), or otherwise $x = 0$. A maximum allowable number of aircraft simultaneously in each sector can then be set as a boundary constraint such that $N_{s,t} \leq N_{Maximum}$.

This maximum allowable number of aircraft simultaneously in each sector ($N_{Maximum}$) is commonly known today as the sector occupancy count, which is used to define the operational capacity limit of each sector, as discussed in Section 1.2.2 and Section 2.6.4. Currently, for ATFCM DCB purposes, for any given time interval t , normally taken as one hour, a priori established $N_{Maximum}$ value for each sector must not be exceeded in order to avoid the overload of ATC workload.

Regardless of being considered the most complete ATFCM macroscopic problem especially due to its extended scope and applicability, the ATFMRP modelling approaches still have some significant limitations when facing the current ATFCM DCB challenges. First, the airspace network capacity is determined by the capacity of individual elementary sectors comprising it. Considering that the capacity of each of these elementary sectors is in turn limited by the tactical ATC workload, the airspace capacity is then managed at tactical level rather than pre-flight (strategic and pre-tactical levels), making these modelling approaches purely reactive in nature. In addition, especially in the European airspace, there is large number of elementary sectors that

need to be implemented within the ATFMRP models, hence leading to tractability and scalability problems, as well as longer computational times to solve the problem efficiently.

Furthermore, in the future targeted seamless airspace environment where a large volume of airspace can be considered as a single sector block [24], the sector capacity limits will be increased considerably and it could then be futile to use a maximum limit sector occupancy count as a hard capacity constraint in this situation. In such an environment, modelling individual airspace sectors could then have little impact on the ATFCM DCB optimisation problem. It is for this reason that, in order to ensure an overall evaluation of the European network performance, a modelling approach considering a consolidated network scheme that takes into account the ECAC airspace in its totality; independent of sector fragmentation boundaries, is proposed in this thesis. This modelling approach is discussed in Chapter 5.

Finally, ATFCM macroscopic approaches are designed to address large-scale scenarios in which aircraft trajectories are represented as aggregated flow. However, they are not able to account for the effects of individual trajectories such as aircraft conflicts [119]. For this reason, flow management microscopic approaches, which mainly focus on aircraft Conflict Detection and Resolution (CD&R), are prominent in the literature.

3.2 Microscopic ATFCM Modelling Approaches

The ATFCM microscopic approaches are currently focused on conflict detection and resolution (CD&R), including sequencing, merging and metering aircraft when competing for limited resources (such as runways and merging points) [51]. The goal is to provide conflict free trajectories for all involved aircraft. A comprehensive survey of CD&R algorithms covering 68 different models is provided by Kuchar and Yang [51]. Kuchar and Yang describes that three well-known techniques exist and can be applied to aircraft conflict resolution; heading changes, flight level changes and speed changes. However, as highlighted in Section 2.3.2, conflict resolution by speed control is rarely applied in current applications. This is mainly due to the limited possible speed changes, which can be achieved by aircraft that are compatible with aircraft performance. Speed

control requires significant anticipation time to be efficient, which is not the case for heading or flight level changes. Consequently, most of the existing research efforts have developed CD&R models that are essentially based on heading and/or flight level changes [120].

Another main reason why speed control is of less interest researched in the literature is the lack of accuracy of trajectory prediction. However, the new developments in CNS and on-board avionics technologies discussed in Section 2.7.4 have opened the door to the application of speed control-based conflict resolution techniques. A review of the most recent SESAR initiatives based on speed control for conflict resolution is provided in Section 3.5.

It is necessary to highlight that CD&R techniques are seldom applied as ATFCM operational solutions to address DCB problems, whereas they are inherently common for ATC reactive/tactical solutions. This is mainly due to the common conceptual approach applied to define and to identify conflicts between aircraft trajectories in these models as discussed below.

The CD&R models define a conflict as a proximity event in which a pair of aircraft experiences a loss of separation by violating pre-determined conventional separation minima standards [121]. For instance, the standards for en-route operations outside Terminal Manoeuvring Area (TMA) at lower altitudes and flight altitudes between FL290 and FL410 for Reduced Vertical Separation Minima (RVSM) airspace require that two aircraft should remain separated from each other by at least 5 NM horizontally (H) and 1000 feet vertically (V) [122]. The result of these standards, is a cylinder commonly referred to as a Protected Zone (PZ) or an airspace volume surrounding each aircraft as illustrated in **Figure 29**, which should not be infringed upon by other aircraft [121].

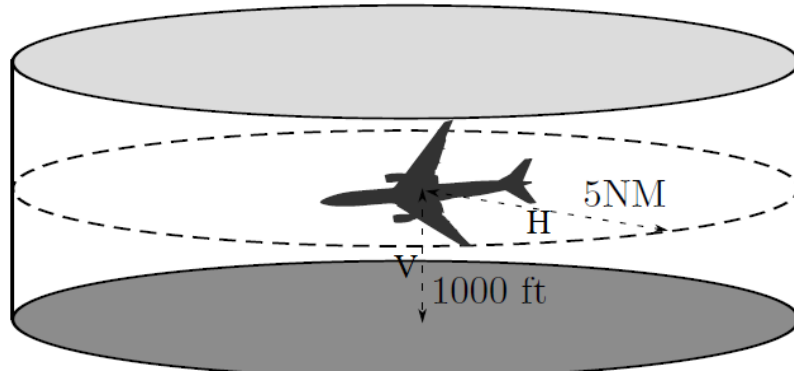


Figure 29: Definition of aircraft Protected Zone (PZ) cylinder for vertical and horizontal separation [121]

To identify aircraft trajectory incompatibility (conflict), the current CD&R models use a geometrical representation of a proximity event between the “intruder aircraft” and the reference aircraft” based on a Lagrangian view (see Section 3.3) of the encounter, in order to characterise and determine the severity of the proximity event. The severity is determined based on the kinematics of the encounter and the minimum separation of the aircraft at their Closest Point of Approach (CPA) [121]. For a conflict to exist, the CPA coordinates must be within aircraft’s PZ, hence infringing the above-defined minimum horizontal (H) and minimum vertical (V) separation standards [121]. To model the aircraft kinematics, **Figure 30** is usually used with the following parameters defined [121]:

- $\vec{V}_r$ is the relative velocity vector between A/Ci and A/Cj involved in a proximity event;
- A/Ci is the reference aircraft considered stationary in the centre of its PZ;
- A/Cj is the intruder aircraft represented as a point and its speed is the relative velocity vector between the two aircraft.

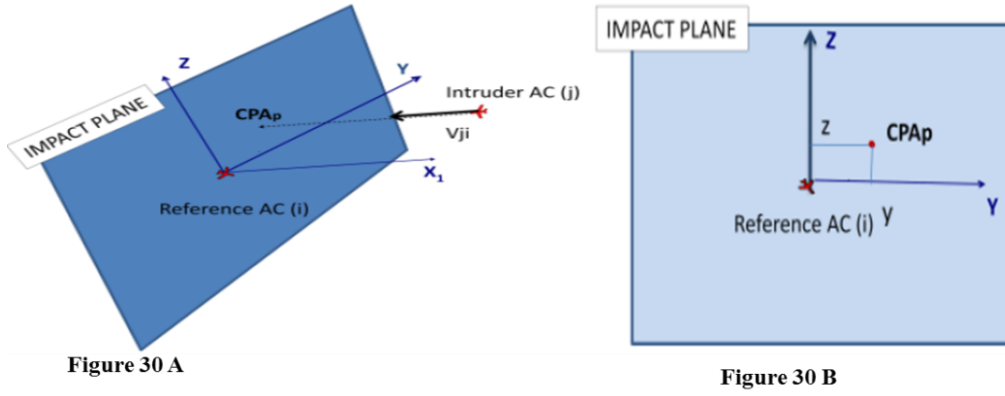


Figure 30: Definition of impact plane and CPA [123]

From **Figure 30**, an impact plane is defined as a projection plane containing the centre of A/Ci and perpendicular to the $\vec{V}_{ji}$. The CPA is then a projected point denoted as CPAp in **Figure 30**, whose coordinates in y-axis and z-axis in a reference frame with its origin at the reference aircraft are determined as the coordinates of the intersection point of the impact plane and a straight line defined using the position of A/Cj in the direction of $\vec{V}_{ji}$. Thus, a conflict will occur if CPAp (y, z) is inside A/Ci's protected zone (PZ) defined by **Figure 29**.

Although the above approach has been widely applied in defining and determining aircraft trajectory incompatibilities [51][124][125], it is hardly adoptable in this thesis due to its several limitations. The first limitation is attributed to the way trajectory incompatibilities are defined based on the CPA coordinates and aircraft's PZ. The conventional separation minima that the PZ definition is based upon were defined based on the Secondary Surveillance Radar (SSR) technology at that time to facilitate tactical conflict detection and resolution in an ATC environment. The approach is, therefore, suitable for ATC reactive/tactical solutions with much shorter available time to react when compared to that of pre-flight ATFCM DCB solutions. When trajectory incompatibilities are identified and mitigated at pre-flight phase to reduce ATC tactical interventions as proposed in this thesis, the criteria should not be based on the conventional separation minima standards, but on the required probability of conflicts that minimise tactical ATCO's interventions.

Additionally, CD&R models based on CPA do not support the application of speed control for conflict resolution. This is because their current formula do not describe how to identify which aircraft (intruder or reference) in the proximity event that needs to speed up or slow down to remove the conflict. This lacking information is important for making speed control conflict resolution decisions. In this thesis, as discussed in Chapter 4 and Chapter 5, small changes to aircraft speed before and after the conflicted junctions are used as the control variables to adjust aircraft's TOAs at those junctions to resolve the conflicts. This requires means to decide which aircraft in the proximity event to speed up or to slow down before and after the conflicted junctions.

Furthermore, when pairwise conflicts are identified by computing their expected separation at their CPA, the variations in their CPA coordinates may not be a major concern when the involved aircraft does not have a common shared point in their expected trajectories. However, when the aircraft shares a common 3D point (junction) in their expected trajectories, the aircraft Time of Arrival (TOA) interval at the junction is a better alternative for determining their trajectory incompatibilities. Any aircraft following a predefined FPL, as defined in its RBT, usually have relevant along-track unpredicted deviations, leading to strong variations on the CPA coordinates, whereas the common 3D point (junction) remains unchanged. Therefore, a definition of “time interval” between arriving aircraft's TOAs at a junction has been chosen to identify trajectory incompatibilities in this thesis as discussed further in Chapter 5.

3.3 New Classes of ATFCM Modelling Approach Based on Lagrangian and Eulerian Dynamics

Recently, new classes of modelling approach in ATFCM based on either Lagrangian or Eulerian dynamics have been introduced [126][127][128]. Lagrangian ATFCM models consider the dynamics of individual aircraft; they can therefore, be seen as trajectory-based models and are microscopic in nature [126]. On the contrary, Eulerian models are aggregated models, which consider the flow rates and densities in control volumes but do not track individual aircraft trajectories [127]. Hence, they are macroscopic in nature.

For Lagrangian models in ATFCM, the dimension of the problem grows proportionally with the number of aircraft considered, since each individual trajectory must be precisely propagated in the network. Hence, Lagrangian models in ATFCM involving large numbers of aircraft are generally computationally intensive [128]. Eulerian models on the other hand, focus on the aggregate properties of the air traffic network and hence, have lower fixed dimensions. As a trade-off however, the Eulerian models are generally not able to provide detailed information about each individual aircraft [128].

Considering the above benefits and limitations of Eulerian and Lagrangian modelling approaches in ATFCM, this research seeks to take advantage of both approaches by providing a combined approach that, to some extent, uses both the Lagrangian and Eulerian views in a complementary manner. This approach enables Eulerian view of aggregate optimal traffic flow to analyze local areas surrounding a conflicted junction whilst also enabling Lagrangian knowledge of individual flight trajectories. The development of this modeling approach is discussed in Chapter 5.

3.4 Modern SESAR's ATFCM DCB Modelling Initiatives

As briefly stated in Section 1.3, according to ICAO Doc. 9854 [9], the modern ATFCM DCB function shall be undertaken at strategic, pre-tactical and tactical levels. At these three levels, all ATM stakeholders will collaboratively participate in providing a methodology, intended to increase the ATM operational effectiveness and efficiency. The last of the above DCB function levels, “the tactical DCB level”, will focus on the following specific objectives [9]:

1. Perform through a collaborative decision-making (CDM) process, dynamic adjustments to the organization of airspace, in order to balance capacity;
2. Perform dynamic changes to the entry/exit times for aerodromes and airspace volumes, and adjustments to the users' schedules.

This thesis aligns with the second objective, which nowadays has led to several other research initiatives as briefly discussed below.

The SESAR dynamic DCB (dDCB) project PJ09 [129], is one of these initiatives. This project aims to improve the ATFCM by reducing the complexity of the expected traffic peaks through the implementation of Short-Term ATFCM Measures (STAM) in order to streamline the ATCOs' workload. In this project, traffic peaks are monitored by Flow Management Positions (FMPs) through parallel use of sector entry counts and occupancy counts. The applied STAM measures include short ground delays and minor re-routings that are applied to a limited number of flights in order to remove the expected demand and capacity imbalance in ATC sectors.

The SESAR's Solution 19 "the automated support for traffic complexity detection and resolution" aims to develop tools for monitoring air traffic demand and evaluating traffic complexity using three different approaches: Algorithm, Cognitive and Convergence-Liapunov [67]. This is another SESAR initiative towards the above second objective. The development of these three approaches have now reached different levels of maturity, and have paved a way for new ideas for practitioners such as the integrated Flow Management Position (iFMP) tool developed in MUAC [67], and for researchers such as intended in this thesis to investigate new methods to reformulate the DCB process.

Other initiatives such as solutions 17, 18, 19 and 37 of SESAR, that are also in line with the above second objective, are discussed in [67]. Solution 19 is of particular interest as it can be considered as a tool, supporting simultaneously STAM and ATC fine-tuned pre-tactical measures for workload balancing at FMP and multisector planner levels [67]. In this solution, similar to the one proposed in this thesis, it is recognised that the need to apply tactical measures and to re-negotiate tactically the RBTs should be considered as exception in the TBO context.

In all the above SESAR research initiatives, strategic de-confliction at hotspots has not been considered. In addition, the applied methods to balance between demand and the system resources to avoid the overload of ATC workload still rely on limiting the maximum expected hourly entry count and or the occupancy of the expected traffic into ATC sectors, irrespective of their interdependencies (conflicts). As discussed in Chapter 1, DCB initiatives that are still based on sector entry count and or occupancy count are

still anchored in the conventional ATM operations “the airspace based operations concept”, and it is broadly recognised that they are no longer efficient to deal with sustained increasing traffic density. It is then necessary to reformulate the ATFCM DCB process in order to align it with the new Trajectory Based Operations (TBO) concept as proposed in this thesis.

3.5 Review of the Current Strategic De-confliction Initiatives

More recently, a few initiatives have considered strategic de-confliction, the “En-Route Air Traffic Soft Management Ultimate System (ERASMUS) project, developed a tool to improve aircraft strategic de-confliction [130][31]. The ERASMUS tool generates a conflict-free trajectory segment of 15 minutes look-ahead time for each flight [130][31]. This is achieved through its Trajectory Control by Speed Adjustment (TC-SA) function, which proposes real-time in-flight adjustments of the RBTs by applying minor aircraft speed adjustments in order to remove detected conflicts and reduce the current ATC workload [130][31].

The key concept of ERASMUS project was adopted by SESAR under the “Trajectory Adjustment through Constraint of Time (TRACT) service project” [99]. It is expected that TRACT service will manage early (within 25 minutes look-ahead time) conflicts. Similar to the TC-SA function, TRACT assesses the expected conflicts within its look-ahead time. It then tries to resolve them by automatically issuing Controlled Time Over (CTO) constraints at the conflicted points to the appropriate aircraft in real time. Minor aircraft speed adjustments are applied to meet the CTO constraints. It has been concluded, however, that a TRACT solution is only possible to solve conflicts involving initial four-dimensional (i4D)-capable aircraft and thus, it is well known that several enablers for TRACT are not yet available [94][131].

The above-discussed strategic de-confliction tools are automated tools that provide strategic detection and resolution of 4D trajectory conflicts at execution/in-flight phase. They are claimed to provide strategic detection of conflicts only because they can detect conflicts at a longer look-ahead time horizon than a typical detection look-ahead time used by the ATCOs. Hence, these initiatives do not meet the main expectation of

SESAR concept for en-route operation stated earlier in Section 1.4.1 as “*the goal of the SESAR concept is to deploy tools to manage complex situations in order to reduce ATC workload by strategic de-confliction measures within the new ATM system*”.

Therefore, it has not been yet described in the literature how strategic de-confliction at pre-flight phase can be achieved, nor elaborated how it should reduce the ATC workload and improve the airspace capacity. This is a major gap between the current initiatives and SESAR expectation; bridging this gap is the focus of this thesis.

3.6 Taxonomy of Tools Used in this Research

As the methodology followed in this thesis is supported by a set of specialised data sources and software tools, it is necessary in this section to provide a brief taxonomy of these sources and tools to form a foundation and familiarization of the discussion in the subsequent chapters.

Demand Data Repository 2 (DDR2): DDR2 is a specialized EUROCONTROL Demand database that contains real historical flight data, airline flight intentions (schedules) and forecasted flight data for all General Air Traffic (GAT) flights within European Civil Aviation Conference (ECAC) area [132]. It also contains data for declared capacity thresholds of most airports in Europe as well as current and future models of European airspace structure.

Historical flight data is sourced from Network Manager (NM) archives. Sources such as Innovata [132], an official source of scheduling reference service, provides early available flight intentions (schedules) from the consolidated airline schedules, while flight intentions for business jets are gathered from organizations such as Avinode[132]. Forecasted traffic information is generated from historical traffic samples adjusted with EUROCONTROL Statistics and Forecast Service (STATFOR) forecast growth factors [133]. Declared capacity thresholds for airports are elicited from sources such as the European Union Airport Coordinators Association (EUACA) [134], whilst airspace network data is sourced from the European route network database [72].

The above data is collected by EUROCONTROL and consolidated into DDR2 to support the NM activities with a controlled access for other users. The DDR2 data can be generated in So6¹⁶ files that can be analysed by other specialised software tools. **Figure 31** shows a summary of sources and data inputs of DDR2 database.



Figure 31: DDR2 data preparation process and data sources [135]

The EUROCONTROL Network Strategic Tool (NEST): NEST is a EUROCONTROL scenario-based modelling engine, capable of enabling a broad range of complex and operationally relevant analysis. It is the official tool used by the NM and the Air Navigation Service Providers (ANSPs) for airspace structure design and development, capacity planning and post operations analysis, strategic traffic flow organization, and for scenario preparation of fast and real-time simulations both at local and network levels [135].

The NEST modelling engine, resulted from the integration of the System for traffic Assignment and Analysis at Macroscopic level (SAAM) tool and the Network Estimation and Visualization of ACC Capacity (NEVAC) tool [135]. It can be used for local analysis at ACC or airport level and for global analysis at ECAC network level. It

¹⁶ S06 is a traffic file which describes for each flight a 4D trajectory in form of a set of consecutive 4D segments from airport of departure to destination.

can process and consolidate large quantities of DDR2 data spanning for multiple years, but also allows for detailed analysis of data to analyse and observe periods of data as small as seconds.

As this thesis largely relies on Fast Time Simulations (FTS) (See Chapter 4), NEST and DDR2 have been selected to enable the development of realistic scenarios for validation exercises, and to enable obtaining results that are operationally realistic. Realistic simulation environments are critical in FTS if the results are to be operationally meaningful. NEST and DDR2 being the official specialised tool and database used by the EUROCONTROL NM and ANSPs in modelling ATM activities for future operations, they provide a realistic simulation environment for this thesis making the obtained results meaningful in ATM stakeholders' perspective. Moreover, DDR2 flight plan data includes all trajectory information required for hotspot identification whilst NEST has a conflict detection function that identifies conflicts within any traffic sample in ECAC airspace.

The ATC Interactive Software (ATC2K): The ATC2K is an interactive software that has been used by aviation training facilities (civil and military) and academic establishments over the years. The tool is able to help the user in efficiently developing air traffic and airspace scenarios for teaching ATC procedural control and for other ATM research purposes [136]. The software is written in 32 bit C++ using Borland CBuilder. The ATC2K uses a simulated Control Working Position (CWP) radar window display illustrated in **Figure 32**, as the Human Machine Interface (HMI) for controlling the air traffic. As shown in **Figure 32**, the window display shows the radar-detected position of flights with correlated flight plan information and the current controller's inputs. Particularly useful for this research, is its Conflict and Risk Display (CARD) feature that displays a table containing all conflicts between aircraft pairs. The information displayed by CARD includes the predicted time of conflict, the identity of involved aircraft and highlights of the route segments in conflict. With this conflict information, users can opt to resolve these conflicts by interactively issuing clearance in form of flight level changes, headings, direct-routes, holdings and speed control.

The ATC2K simulator is used in this thesis to simulate and analyse conflict detection and resolution of the preliminary test scenarios presented in Chapter 6. Using its interactive HMI, the ATC2K enables to apply the computed optimal speed/TOA changes (See Chapter 6) on the speed profiles of aircraft identified by CARD in the simulated traffic scenario to be in conflict. Through its CWP radar window, the dynamics of the involved aircraft before and after speed/ TOA changes are applied can be visualised and compared. Therefore, the ATC2K simulator provides a dynamic interactive environment for preliminary verification of speed/TOA changes in resolving the detected conflicts.

EUROCONTROL Base of Aircraft Data (BADA): BADA is a widely used aircraft performance model, developed and maintained by EUROCONTROL in collaboration with different aircraft manufactures [137]. It is mainly designed for trajectory modelling especially for Trajectory Prediction (TP) simulations and analysis to support advanced ATM concepts. BADA datasets are available as a collection of ASCII files¹⁷, which specify the operational and procedural performance parameters for 519 different aircraft types including all Airbus and Boeing aircraft families [[137]. Accordingly, it is currently recognised as an international standard aircraft performance model for ATM applications.

Several aircraft performance models have been widely described in the literature, a review of these models is provided in [138]. Aircraft performance models are essentially parametric and they rely on the corresponding aircraft flight dynamics. The flight physics of the aircraft dynamics is mainly concerned with the performance, stability and control of aircraft as well as the relationship between the physical characteristics of aircraft and its evolution in air [139].

Depending on the required level of fidelity, flight dynamics models are typically formulated either in 6-Degrees-of-Freedom (6-DoF) equations that consider both three force equations and three moment equations, or in 3-DoF equations that ignore the rotational momentum [140]. The 6-DoF-based models are usually developed in studies that require high fidelity modeling such as the controllability of aircraft in response to the airspace environment. These models are the basis of the modern Flight Management System (FMS) development [140]. For ATM applications that involve mostly commercial airlines, the reduced 3-DoF equations of motion are most prominently accepted [138]. The 3-DoF-based models are also commonly referred to as Point-Mass Models (PMM). The BADA model is based on a PMM total-energy model, which equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy [138]. A complete description of BADA PMM total-energy model is provided in [137].

¹⁷ ASCII file: Is a text file in which each byte represents one character according to the ASCII code

The BADA model is used in this thesis to analyze the effects of the proposed method on the flight operating costs. The model is used to extract aircraft performance data used to compute fuel consumption for different test scenarios in Chapter 6.

The Air Traffic Forecasting Model: The validation of the proposed ATFCM DCB method is analysed considering scenarios for both current and forecasted air traffic densities in the ECAC airspace. Therefore, use of reliable air traffic forecast is necessary in this thesis. The main consideration in performing a forecast is its intended use. Depending on the intended use, air traffic forecast can be generated considering different time horizons (short-term, medium-term and long-term), of which the length may vary from one forecasting tool to another [141]. The type of the output, the level of output details and the granularity of the method used vary depending on the intended use of the forecast. In this thesis, forecasted air traffic is used as a representative of future demand in ECAC airspace, in order to analyze the performance of the proposed ATFCM DCB method in the future at 6 year look-ahead time horizon. To enable detailed identification and mitigation of conflicts, a detailed level of air traffic forecast data including a set of each flight information and trajectory parameters is required.

There are three main air traffic-forecasting methods [141]:

1. Quantitative or mathematical;
2. Qualitative or judgemental;
3. Decision analysis (combination of quantitative and qualitative methods).

Air traffic forecast techniques that generates forecast based on enriching a historical traffic sample through implementation of certain rules and constraints, are quantitative forecasting methods [141]. Qualitative methods on the other hand involve all techniques applied in situations where a reference historical traffic sample is not available or applicable, requiring the use of experience and judgment [141]. In some situations, depending on the intended use, a reliable forecast can only be obtained through the application of a combination of quantitative and qualitative techniques (decision analysis method).

Figure 33 shows different alternative forecasting techniques available for each of the above methods. From these techniques, the quantitative methods using Trend Prediction (TP) and/or econometric analysis forecasting techniques are the most popular techniques used in ATM related forecasts [141]. Therefore, only these two techniques are further discussed in this thesis, where detailed descriptions of all other techniques are provided in [141].

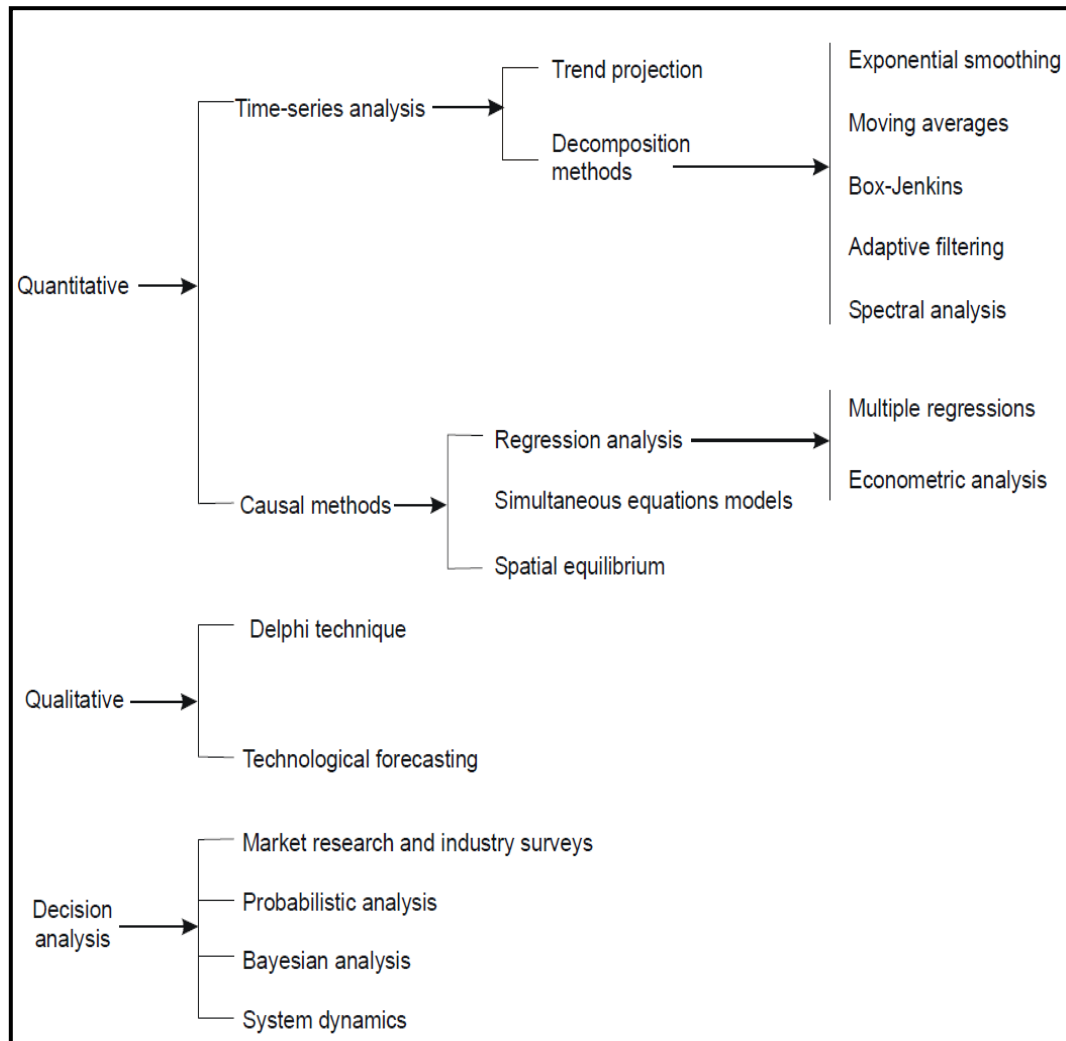


Figure 33: Different alternative forecasting techniques [141]

The TP technique is based on time-series analysis, which relies on the availability and the accuracy of the historical data. Time-series analysis assumes that historical patterns of that data will continue in the future [141]. In TP forecasting technique, past air traffic

growth trends are simply extrapolated based on the historical data. Thus, the suitability of using this technique relies on the forecaster confidence that the assumption of the continuing trend when applied to a certain operating environment will prevail. This approach is then more suitable in forecasting for short-term horizons, where the extrapolation can be applied considering modified growth rates that account for short-term disturbance in the underlying trends. The TP technique does not explicitly take into account the way in which other factors such as the economic, social and operational conditions may affect the traffic forecast [141]. As these underlying causal factors usually change in medium and long-term forecasting horizons, the extrapolation used in TP is likely to be unreliable and theoretically difficult to substantiate in these time horizons.

For medium and long-term forecasts, econometric analysis is the most used technique in ATM [34][142][143]. It is a multiple regression analysis based on causal methods (cause-and-effect relationship). In contrast to a single independent variable (traffic variable) used in the TP analysis, econometric analysis takes into account multiple independent variables that are considered to have a causal relationship with the traffic demand. These generally include economic, social and operational conditions that affect the development of traffic. The econometric model attempts to explain the demand for air travel as being caused by changes in these independent variables. It is convenient to identify four major steps involved in an econometric forecast, although they may not necessarily be performed independently from each other [141]. The steps are:

1. Selection of relevant independent variables (causal factors);
2. Formulation and modelling of the relationship between the above variables and traffic demand;
3. Perform analysis to test the above relationship (usually by statistical measures);
4. Develop forecasts of future scenarios for the independent variables from which the traffic forecast is subsequently derived.

Several prominent air traffic-forecasting models/tools based on econometric analysis have been developed; these can be grouped as follows:

1. The general ICAO forecasting model developed in collaboration with ICAO Regional Traffic Forecasting Groups (RTFGs): Asia/Pacific (APA-TFG), Caribbean/South America (CAR/SAM-TFG), Middle East (TFSG) and Africa/Indian Ocean (AFI-TFG)) [141];
2. Models developed by individual ICAO contracting states such as the Passenger Origin-Destination Model (PODM) developed by Canada statistics and forecasts branch of transport [142], and the UK Department for Transport (DfT) aviation forecasting model, developed to produce forecasts of UK air passengers and air transport movements (ATMs) [143];
3. Models developed by other organisations such as EUROCONTROL Statistics and Forecast (STATFOR) model [141].

The ICAO general forecasting model uses econometric analysis to estimate passenger numbers and freight volumes in major regional route groups and major city-pairs at long-term look-ahead time horizons. The causal factors for this model are the world Gross Domestic Product (GDP) and airline yields. The World GDP, which is the broadest available economic indicator, is used to estimate the impact of economic, demographic and income factors on passenger numbers and freight volumes [141]. The airline yields (revenue per passenger-kilometre) are used as a proxy for average airline fares [141]. The forecast of this model is generalised and not sufficiently detailed to support an analysis at a level of conflict identification in ECAC airspace required in this thesis. In fact, this forecast is more effective for government strategic planning intended to determine the level and direction of capital expenditures, and to evaluate alternative policy scenarios and their impact on aviation activity at global and regional scales.

For the national level models, methodologies and assumptions are tailored towards forecasting national air passenger demand and national air traffic movements (ATMs). These models are also based on the econometric analysis technique [142][143]. In these forecasting models, the dependent variables are ATMs and number of national air passengers, whilst the causal factors are the national GDP, national exports, imports and airline fares. The forecast of these models is generated at both national aggregate level and airport level. These national level models also do not provide detailed air traffic

forecast that may include routes and other detailed flight information required in this thesis. They are instead more suitable for national aviation policy development and for airport planning purposes.

For forecasts developed by other organisations other than ICAO and national organisations, the EUROCONTROL Statistics and Forecast (STATFOR) forecasting model is the most popular [133]. The STATFOR forecasting model is the official model used in Europe at a regional level [133]. It is tailored to produce forecasts to support both planning and monitoring of the ATM system in Europe. Thus, the model forecasts flight details rather than passenger numbers and freight volumes.

The forecast is performed in three look-ahead time horizons: Short-term (up to 24 months), medium-term (up to 6 years) and long-term (up to 20 years). For each look-ahead time horizon, a different forecasting method is applied. The short-term forecast is produced through time-series analysis (TP technique) which takes historical traffic trends as the input. The trends are then adjusted for any errors and abnormal events, and the forecast is performed using a pre-selected auto regressive integrated moving average (ARIMA) to produce traffic predictions at horizons of 1 to 24 months [141]. Thus, a STATFOR short-term forecast is good at capturing recent trends month by month and projecting these trends into the immediate future, up to two years ahead.

The STATFOR Mid-Term Forecasting (MTF) method is a blend of both TP techniques for modelling of recent traffic trends and econometric analysis to capture future traffic demand based on other causal factors. The TP in this model considers past patterns of traffic growth, seasonality, one-off-events and early available airline schedules for the coming months. The econometric model is developed by growing a baseline traffic (all IFR flight movements in ECAC airspace for a given period of up to 6 years), taking into account the economic growth, past patterns of supply, the growth of low-cost carriers, influence of high-speed trains, passengers models, load factors and aircraft size [141].

Figure 34 shows an overview of the STATFOR-MTF generation process.

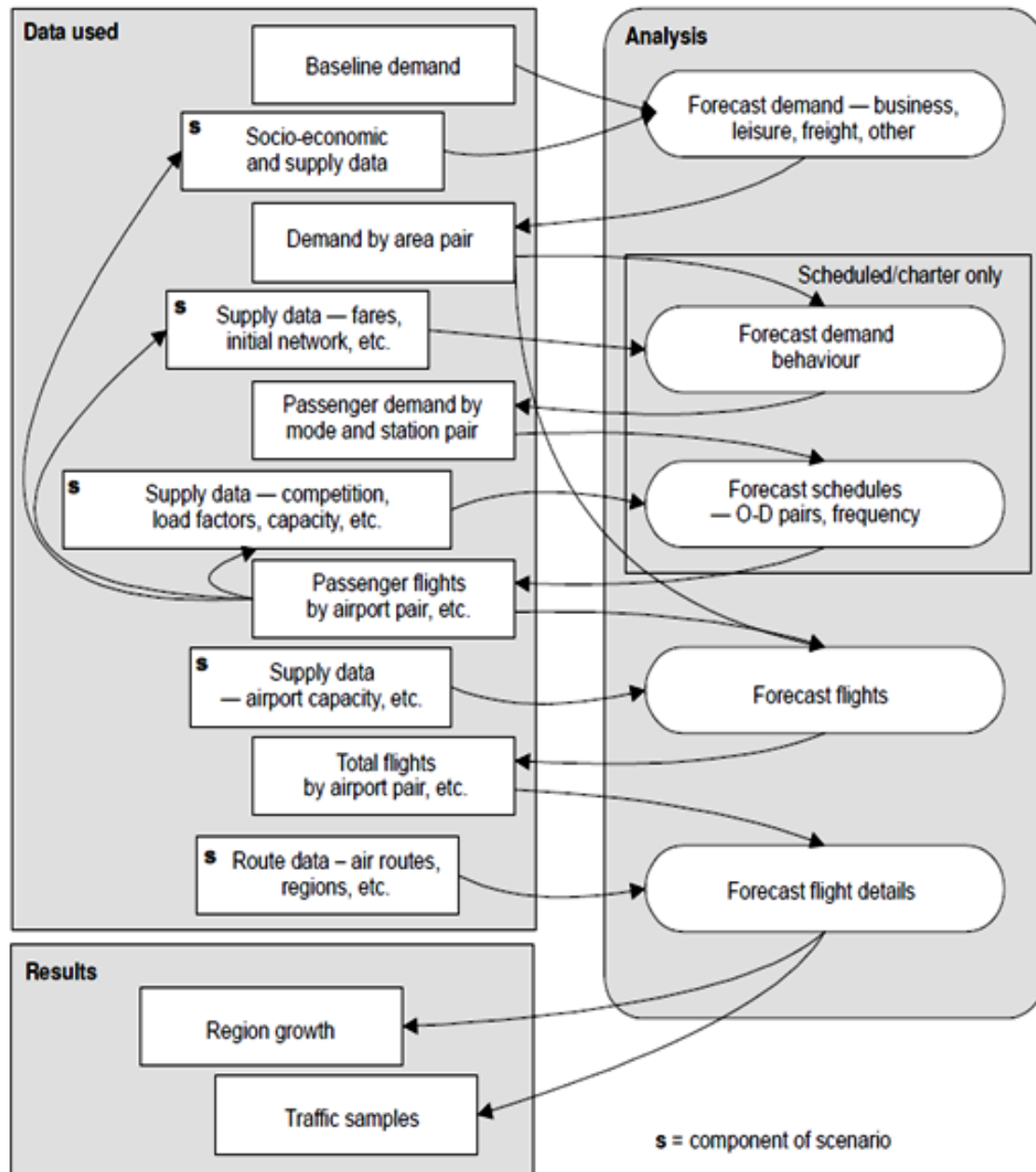


Figure 34: STATFOR medium-term forecast generation process [141].

Using NEST analysis tools, the results of STATFOR MTF can be either constrained or unconstrained by the declared annual airport capacities to provide forecasts at different levels of details. A combination of NEST and STATFOR MTF provides forecasts at both aggregate level such as traffic between airport-pairs and at detailed level where the traffic forecast is mapped onto the airspace network to give flight counts in the airspace, including a detailed set of each flight information and trajectory parameters.

The STATFOR long-term forecast (LTF) is not discussed in this thesis as it is still under development and is not yet operationally usable [141].

This thesis uses a combination of NEST and STATFOR MTF to forecast a traffic density scenario in ECAC for year 2022 (see Chapter 7). This forecasted scenario is used to test the performance of the proposed ATFCM DCB method in the future. A combination of NEST and STATFOR MTF enables to generate a forecasted traffic sample where each trajectory is provided in the same data format as that of the planned trajectories of the current traffic in ECAC based on which the forecast is interpolated from, as further discussed in Section 7.4.3.

4 RESEARCH CONTEXT IN TRAJECTORY BASED OPERATIONS AND METHODOLOGY

This chapter describes the operational environment considered in this thesis including the context in the Trajectory Based Operations (TBO), the airspace environment and all the corresponding assumptions made. It is then followed by the description of research methodology used to achieve the research objectives.

4.1 The New ATFCM Method in TBO Concept

A key pillar required for the implementation of the proposed Air Traffic Flow and Capacity Management (ATFCM) Demand and Capacity Balancing (DCB) method is to use the aircraft Reference Business Trajectory (RBT) as the basis for the ATFCM DCB solution. Under the TBO concept, the aircraft predicted trajectory must be considered for its whole life cycle, starting from when it is shared as the Shared Business Trajectory (SBT) to the fully completed trajectory in block time. The trajectory management under TBO is performed at pre-flight phase (operational planning) in the form of Trajectory Management (TM) by the ATFCM system and at tactical level (during the flight operation) in the form of Separation Management (SM) by the Air Traffic Control (ATC) system.

The role of the ATFCM DCB method proposed in this thesis within TBO concept is to act as glue between the pre-flight and tactical levels in order to close the current gap between the ATFCM TM and the ATC SM functions discussed in Section 2.4.3. The proposed method plays a role of TBO-based Short-term ATFCM Measure (STAM) by synchronising the trajectory prediction and ensuring consistency between the trajectory and the generic constraints, originating from various ATM components at different planning and execution levels. It also involves a coordination of trajectory predictions and trajectory constraints between the pre-flight TM and the tactical SM levels as well as among all involved operational ATM stakeholders at these levels. This process can be seen as the process to produce RBTs from associated SBTs, as depicted in **Figure 35**.

The synchronisation of each planned aircraft trajectory (and its constraints) at both pre-flight and tactical TBO levels by all relevant ATM stakeholders as illustrated in **Figure 35**, will increase their awareness and enable them to anticipate better the events that may affect them. Operating in such a TBO environment will give all stakeholders a clear visibility of the aircraft 4D trajectory and/or the generic constraints that define it, as well as the operational factors that may affect it.

Since the synchronisation of information across all operational stakeholders enables them to anticipate many issues early on including the possible bottlenecks in separation provision, it is a pre-requisite for TBO. Therefore, SWIM is important in this operational environment. An early identification of issues increases the solution space for solving them, enabling the airspace users to plan their operations better. The Flight Operation Centers (FOCs) who have full awareness of the attributes of each flight, are key stakeholder in this process.

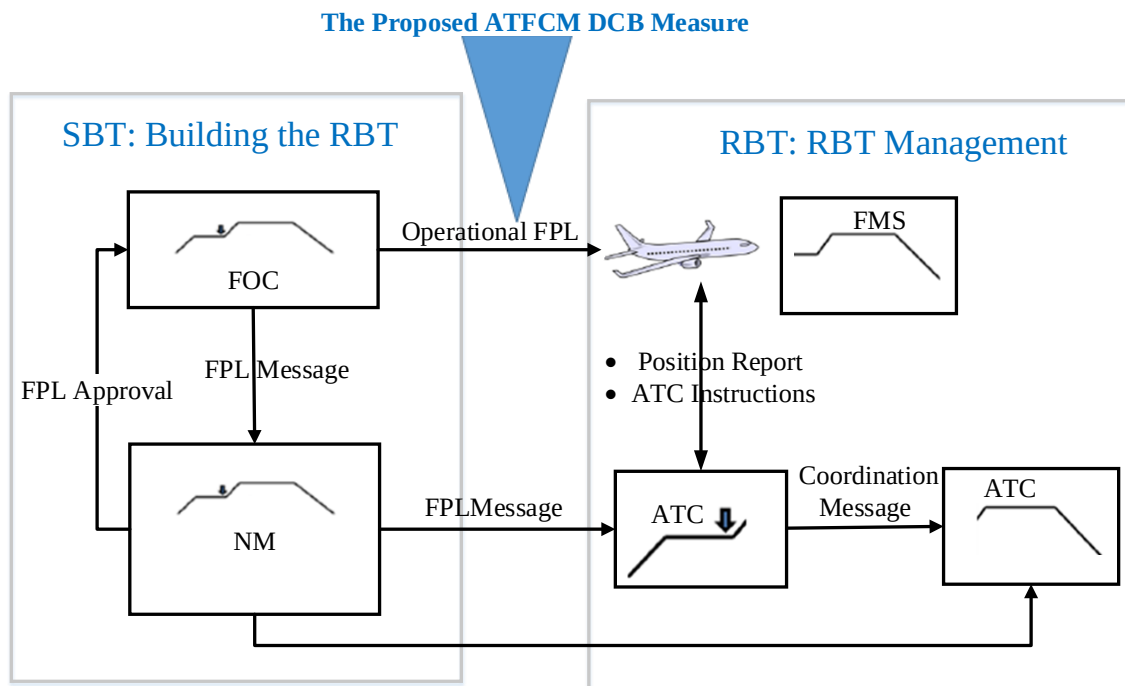


Figure 35: Considered TBO operational environment

The proposed ATFCM DCB method enables the Network Manager (NM) to include specifications of time constraint in the RBTs as far in advance as possible in order to deliver a de-randomised and well-behaved (conflict free) traffic to the tactical level.

These time constraints are issued to reduce the ATCOs' SM interventions whilst allowing the AUs to maximise adherences to their desired trajectories (represented by their RBTs containing reasonable time constraints) for the whole traffic network.

In this thesis, the term "Traffic" is defined as a dynamic Spatial-Temporal (S-T) distribution of more updated and reliable planned trajectories (updated from SBT to RBT), where the ATFCM DCB function is focused on the analysis of these planned trajectories' S-T interdependencies that are likely to involve ATCOs' SM interventions. This shifts the DCB focus towards improving the ATM system's predictability by exploiting the existing gap between the present-layered ATM pre-flight ATFCM DCB and the ATC tactical management. However, the pre-flight analysis of S-T interdependencies is subjected to relevant uncertainties, which affect the degree of adherence of the actual to the planned trajectory at this long look-ahead time horizon. Therefore, the existing level of uncertainties in the trajectory definition at pre-flight phase is considered in this thesis. It is assumed that the accuracy of 4D trajectory information is enabled by the availability of the enhanced communication, Navigation, Surveillance and aircraft Avionics (CNS+A) capabilities defined by ICAO under the Performance Based Navigation (PBN) concept's targets [25]. These PBN targets such as RNP 1 in en-route ECAC airspace and availability of Controlled Time of Arrival (CTA) on board aircraft, supports improved 4D navigation of flights to achieve the levels of uncertainties considered in this thesis as further discussed in Section 5.5.

4.2 Airspace Operational Environment

The proposed ATFCM DCB method should be applicable in both the conventional structured route network and the airspace environments enabling a full implementation of Free-Routing Airspace (FRA) [98].

To ensure an overall evaluation of the European network performance in both airspace environments, a consolidated network scheme that considers the European Civil Aviation Conference (ECAC) airspace in its totality independent of flight information regions (FIR) and sector boundaries is used in this thesis. This is in line with the ICAO airspace operational target requirement that states, "*The airspace shall be organized to*

facilitate the seamless handling of flights and the ability to conduct flights along optimum flight trajectories, without undue restrictions or delay resulting from any airspace fragmentations” [9].

To simplify the analysis and discussed further in Section 4.3 bellow, this new ATFCM DCB method assumes that the current Semi-Circular Rule (SCR) is sufficient to ensure vertical separation. Furthermore, only traffic operations beyond the limit of Terminal Manoeuvring Areas (TMAs) in the ECAC airspace are considered for the implementation in this thesis. Finally, given the current lack of real information about the Airspace User (AU) preferences in a FRA environment, direct routes are considered as the synonym for free-routes.

4.3 Research Main Assumptions

Derived from the operational environments discussed above, the following main operational conditions and aircraft and systems capabilities are assumed to limit the scope and to substantiate the methods applied in this thesis:

1. System Wide Information Management (SWIM) is available and operational for 4D trajectory information sharing as required by SESAR for full implementation of TBO [94];
2. The NM and AUs have all the technical capabilities required for SBT pre-flight negotiation up to the agreement of RBT. These technical capabilities shall include all the target ATM communication technological enablers (See Section 2.7.4) that provide the type of information required for a CDM based negotiation of RBTs;
3. The availability of advanced technology enablers defined by SESAR as pre-requisites for TBO including data-link, Automatic Dependent Surveillance-Broadcast (ADS-B) and Advanced Flight Management System (FMS) which allows each aircraft for precise positioning, timing and guidance along agreed RBT [101];

4. A seamless ECAC airspace with its Unified Flight Information Region (UFIR) as required by ICAO airspace operational target requirement (See Section 4.2) [9];
5. Only traffic operations beyond the limits of TMAs in the ECAC airspace are candidates for the implementation of the new ATFCM DCB method (the DCB solutions will not be affected by flight operations in the TMAs). This assumption limits the scope of the proposed method to en-route ECAC airspace where most aircraft will have enough anticipation time for realistic application of speed control for de-confliction as discussed in Section 5.1;
6. System performance of Required Navigation Performance (RNP 1) capability is applied for all en-route ECAC operations which require lateral Total System Error (TSE) of ± 1.0 NM accuracy for 95% of flight time. In the lateral dimension, adherence of the aircraft's current position is bound by the RNP specification the aircraft flies to [25]. Therefore, a low RNP value is a main enabler of the TBO in en-route airspace;
7. The SCR procedure is used to provide sufficient vertical separations between aircraft flying in the opposite direction with Reduced Vertical Separation Minima (RVSM) rule applied in the whole considered airspace. As discussed in Chapter 5, this assumption enables to exclude from the scope of the research problem all conflicts involving aircraft that do not share any active junction, enabling realistic application of aircraft pre-flight de-confliction methods proposed in this thesis;
8. Direct routes (great-circle distance or orthodromic distance) are considered as a simplification of free-routes in a FRA environment. In FRA, it is not yet possible to know in advance which route the user would choose for a flight due to multi-option direct routings that maybe be available to them [53]. However, since users are more likely to choose the most optimal among all the direct routes available, it can be reasonably assumed that the shortest route (great-circle distance) is the most optimal available route that will be selected by most users.

4.4 Research Methodology

The methodology followed in this thesis consists of several fundamental methods that are applied to achieve the research objectives. **Figure 36** shows an overview of this methodology, which is divided into four research phases, alongside the specific methods applied for each phase. The thesis chapters that cover the discussion of each phase and the research objectives (RO) for each phase are also shown in the diagram. The dotted arrows shown in **Figure 36** illustrate the research progression between research phases and their different internal stages whereas the solid lines link the designated chapters, the objectives and the methods to each respective research phase.

4.4.1 Research Phase 1- Familiarisation and Literature Review:

This research phase forms the baseline of the research. It consists of a background to the problem, followed by a comprehensive review of the ATFCM DCB problem scope in the context of both conventional and future ATM operational concepts. This review provides an understanding of the main research issues and concepts as well as includes a critical review of state-of-the-art ATFCM DCB optimisation problems and new regulatory ATFCM DCB initiatives. The review enables the thesis to identify the research gaps and the research novelty, which then leads to the formulation of research problem stated.

This phase also involves the selection and familiarisation of the specialised data sources and software tools applied in the thesis to support the research methodology. Descriptions for each topic covered in this phase are written in Chapters 1, 2 and 3.

4.4.2 Research Phase 2- Description of the Operational Environment and Research Main Assumptions

Based on the identified research gaps in phase 1, Research Phase 2 starts with a description of operational environment considered for the application of proposed ATFCM DCB measure. From this description, a set of main operational assumptions, aircraft's capability assumptions and systems' capability assumptions made for realistic application of methods applied in this thesis are identified.

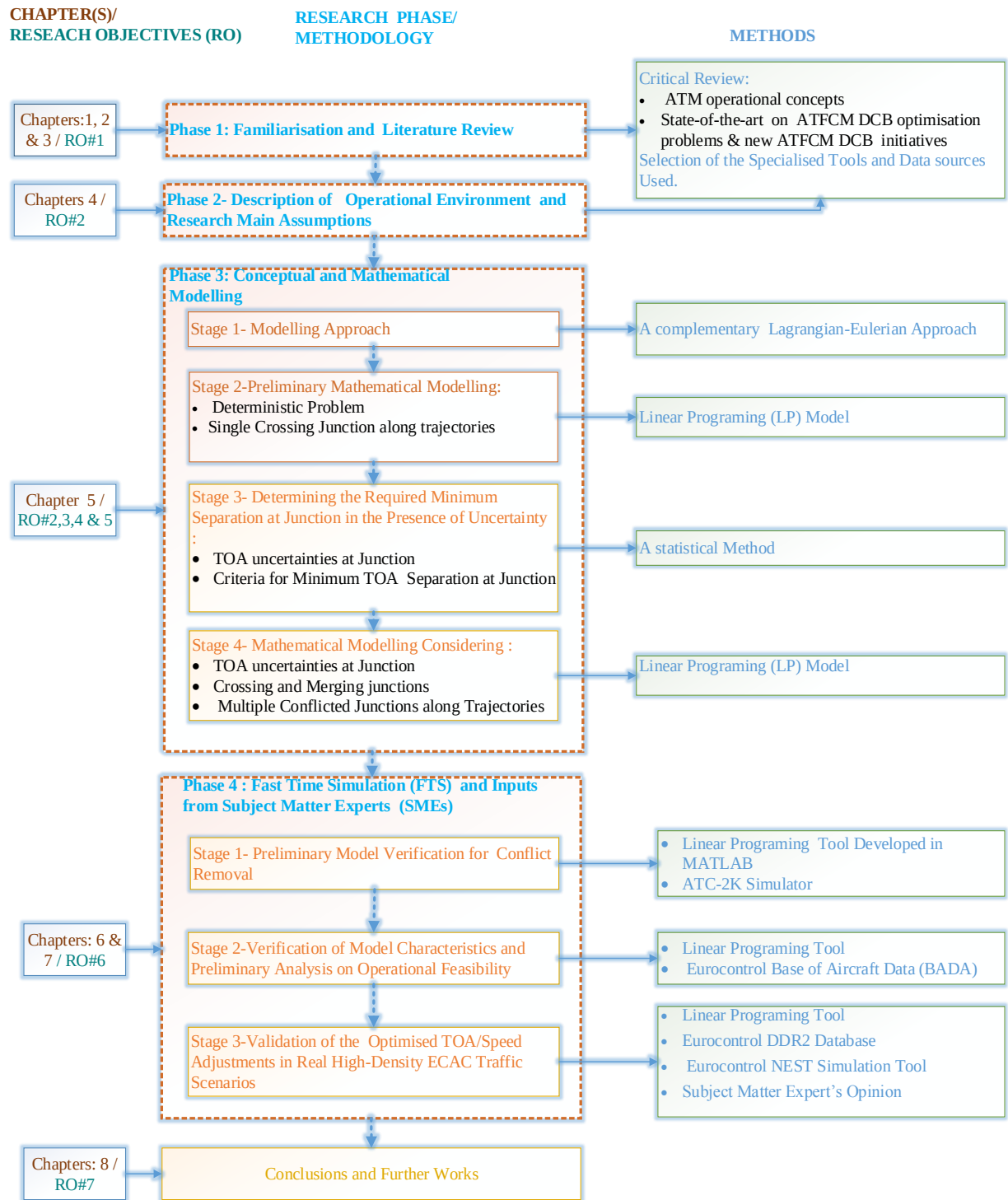


Figure 36: Summary of the methodology followed along with specific methods applied

4.4.3 Research Phase 3- Conceptual and Mathematical Modelling:

This phase forms the first core part of the research. It comprises four sub-stages as shown in **Figure 36** and described as follows:

Stage 1- Modelling Approach: This first stage of Phase 3 concerns the characterisation of the research problem in the operational environment described in Phase 2. This is achieved through conceptual modelling and definition of the main elements necessary to formulate mathematically the research problem.

The key to this stage is the definition of the proposed new ATFCM DCB concept, stated as “reducing the probability of ATCO tactical SM interventions by hotspot identification and mitigation at pre-flight phase using optimal changes on the aircraft’s Times of Arrival (TOA) at crossing or merging points (junctions)”. The definition of this new ATFCM DCB concept is fundamental for the conceptual modelling of the problem.

A “hotspot” is defined based on the modelled airspace topology and junction topology, and is characterised by applying a Lagrangian-Eulerian modelling approach. Considering the benefits and limitations of Lagrangian and Eulerian ATFCM modelling approaches identified in Chapter 3, this thesis applies a combined conceptual modeling that to some extent uses both the Lagrangian and Eulerian views in a complementary manner. This enables to combine an Eulerian aggregate optimal traffic flow view to analyse local areas surrounding junctions with the Lagrangian knowledge of individual flight trajectories. In this context, the geometric characterisation of junctions (Lagrangian view) is used to enable tracking the entire trajectory of each aircraft in order to identify conflicts, and to enable the computation of speed/TOA changes required for each aircraft for conflict removal. Each conflict is identified by measures of aircraft TOA separation at the junction. On the other hand, an aggregated local Eulerian view is used as a metric to measure the complexity of the local area where the conflict is located.

Stage 2-Preliminary Mathematical Modelling: To avoid the limitations of the Closest Point of Approach (CPA) based conflict resolution approach discussed in Chapter 3, a time separation between aircraft TOAs at the junction is used to formulate a cost function for conflict resolution. This cost function relies on a Linear Programming (LP) optimisation model that seeks to minimise the total aircraft speed/TOA changes required for conflict removal while maintaining all aircraft departure and their Targeted Time of Arrival (TTA) at destination waypoint. In order to keep the entropy of the traffic in the route network, the global time performance at each active junction is also maintained. This LP model removes the scalability problem inherent in the existing ATFCM optimisation methods, especially when applied to high-density traffic situations such as that usually in the ECAC airspace.

In order to implement the conflict resolution model on realistic air traffic scenarios, the aircraft separation, required for conflict removal and achieved by speed/TOA control, is treated as an optimisation problem that has the following objectives:

1. Maximise the total number of conflicts removed by means of the speed/TOA changes;
2. Minimise the total amount of speed/TOA changes used for the conflict removal.

This LP optimisation problem is formulated by considering first, a simplified version of the problem and later extended to consider the full extent of the problem. At this preliminary mathematical modelling stage, a preliminary LP optimisation problem is formulated by considering only a single pairwise crossing junction along the aircraft trajectories in a deterministic environment.

Stage 3-Determining the Required Minimum Separation at Junction in the Presence of Uncertainty: In the proposed ATFCM DCB method, the identification and mitigation of conflicts are performed at pre-flight phase using the planned trajectories (i.e. RBTs) as the input. Although the RBTs could be optimised to incorporate uncertainties in terms of meteorological conditions at this level as proposed by recent researchers [144], this thesis applies a moderate approach that the uncertainties in the trajectory definition still exists and cannot be omitted. Therefore, this Stage 3 of phase 3 describes the

determination of aircraft's TOA uncertainties at a junction (considering the cross-track, along-track, vertical and scheduling TOA uncertainties at the junction) which are modelled in Section 5.3 using a statistical method.

The determined level of TOA uncertainties is then used to establish a criterion for minimum pairwise TOA separation at junction (trajectory compatibility condition) whilst also considering the required probability of aircraft simultaneous arrival at junction that minimises the ATC tactical interventions. The minimum pairwise TOA separation at junction is then used in turn to determine the junction's inbound capacity. This inbound capacity is defined as an indicator of airspace capacity.

Stage 4-Mathematical Modelling for Merging Conflicts and Multiple Conflicted Junctions along Trajectory: Based on the established trajectory compatibility condition at junction in the presence of uncertainty defined in stage 3, an LP problem is formulated in stage 4 considering the effect of these uncertainties. The LP model also extends the scope of the preliminary LP model developed in Stage 3, from a single crossing junction problem to a problem that includes situations of multiple aircraft conflicts at the junction (merging conflicts) and situations that involves multiple conflicted junctions along the aircraft trajectory. This problem covers all possible conflict situations considering all the assumptions made in this thesis.

4.4.4 Research Phase 4: Fast Time Simulations and Inputs from Subject Matter Experts

This research phase focuses on the use of Fast Time Simulations (FTS) and subject matter experts' inputs, to verify the models developed in Phase 3, and to validate both quantitatively and qualitatively the proposed ATFCM DCB method. This phase consist three progressive verification and validation stages in which several test scenarios are developed, simulated and analysed.

Fast Time Simulations (FTS): In FTS, the validity of results is largely determined by how realistic the simulation environment and the model inputs are. For this reason, specialised and operational ATM simulation platforms and real trajectory data sources

such as the EUROCONTROL Network Strategic Tool (NEST) simulation platform, Base of Aircraft Data (BADA) flight performance model and EUROCONTROL Demand Data Repository 2 (DDR2) flight database, which are discussed in Chapter 3, are used for verification and validation exercises in this thesis. These are the official simulation tool, model and flight database used by the European ANSPs and by NM.

In addition, FTS allows a greater flexibility in simulating air traffic operations since it facilitates a progressive investigation and quantitative analysis on a wide range of model characteristics, and their possible impact on the results. To this end, several scenarios are progressively developed and simulated in this phase. The simulation results are discussed and critically evaluated in relation to the expected performance of the model, within the context of the considered operational environment and research assumptions.

Inputs from Subject Matter Experts (SMEs): In addition to the FTS based quantitative validation analysis, given the complexity of the ATM operations that involve different stakeholders, it is necessary to consider experts' opinions from various ATM stakeholders to complement the quantitative analysis. The expert's input is important in the qualitative analysis of the operational feasibility of the proposed ATFCM DCM method because it helps to indicate the level of acceptability of the proposed method from the perspective of different ATM stakeholders. To obtain SME's opinion, a small-scale questionnaire was answered by different ATM experts representing different ATM stakeholder groups including Airspace Users, Network Managers and ANSPs.

Stage 1-Preliminary Model Verification for Conflict Removal: At this first stage of Phase 4, two scenarios are simulated and analysed. The simulation is performed using an LP optimisation tool developed in MATLAB and the ATC2K simulator (see Section 6.1). The first scenario is concerned with the model verification of conflict removal using optimal TOA/speed changes for a single pairwise crossing junction which is considered as a deterministic scenario. The conventional separation minima are used to derive the trajectory compatibility criterion at junction (See Section 6.1).

Following the model verification in a deterministic scenario, the second scenario looks into the trajectory compatibility criterion as the minimum required TOA separation at junction (derived in Phase 3). This minimum TOA separation at junction is derived based on the modelled TOA uncertainties at junction and the required probability of aircraft simultaneous arrival at junction. This scenario also considers situations of merging conflicts at single and multiple junctions along the aircraft trajectory, in addition to the single crossing junction scenario considered in the first scenarios. With this scenario, the scope of the solution encompass the conflict removal of all possible geometries of conflicted junctions (see Section 5.1.1), along the entire trajectory of each aircraft in the considered airspace environment.

The simulation results at this stage are used to conduct a preliminary analysis on the possibility of conflict removal at pre-flight phase using optimal TOA/speed adjustments with and without the effects of aircraft TOA uncertainties on aircraft separation at junction.

Stage 2-Verification of Model Characteristics and Preliminary Analysis on Operational Feasibility: The simulations at this stage are performed using the LP tool and EUROCONTROL Base of Aircraft Data (BADA).

The first scenario at this stage is simulated to verify the LP model characteristics at different traffic densities. It is particularly used to establish the number of aircraft in a set, inbound a junction in a given period of time that can be realistically (in terms of speed/TOA changes) de-conflicted at pre-flight phase. This simulation also enables establishing what junction's throughput can be achieved without exceeding pre-determined realistic maximum speed/TOA change thresholds. The maximum junction throughput can be used as an implication of the overall operational airspace capacity.

The second scenario is simulated to analyse the behaviour of LP model in situations where the arriving traffic demand exceeds the junctions inbound flow capacity. The results indicate the monotonic increase (always increasing and never decreasing) of speed/TOA changes for some aircraft when the arriving traffic demand exceeds the

junction's inbound flow capacity, and provide the basis for the following feasibility analyses:

1. Identification and analysis of the operational and traffic situation conditions that allow a modulation of speed/TOA changes among all aircraft, to enable some level of fairness in TOA/Speed required of all aircraft ;
2. Establish conditions under which steady state speed/TOA changes are achievable.

The last scenario at stage 2 of phase 4 is used to analyse the effects of the proposed ATFCM DCB method on the flight operating costs. The BADA database is used to extract the aircraft performance data used to compute aircraft extra fuel consumption due to TOA/Speed changes, considering different traffic demand and conflict situations.

Stage 3-Validation of the Optimised TOA/Speed Adjustments in Real High-Density ECAC Traffic Scenarios: This is the final stage of Research Phase 4. The simulation includes real high-density ECAC scenarios, used to validate the pre-flight optimised TOA/Speed adjustments as an ATFCM DCB solution. The simulation exercises are performed using the LP tool, DDR2 database and NEST simulation platform.

Historical DDR2 flight plans on a specific date are used to create network benchmark scenarios in the NEST simulation platform. A conflict analysis tool in NEST is used to identify conflicts in the scenarios. Optimal speed/TOA changes are then computed using the LP model and applied to the aircraft's nominal flight speed profiles in the benchmark scenarios to produce "revised" network scenarios with speed profiles optimised for free-conflict. The optimised scenarios are then analysed using NEST for conflict identification to establish a comparison between the benchmark and the optimised scenarios in terms of number of conflicts detected. The simulated scenarios include:

1. Current ECAC high-density traffic scenarios based on the 2016 flight plan data;
2. A future high-density traffic scenario developed using a combination of NEST and STATFOR MTF forecast for 6 years look-ahead time horizon.

This stage also involves simulations exercises performed to analyse the following:

1. The Effect of aircraft departure time uncertainty on the pre-flight de-confliction in ECAC area;
2. Quantitative and qualitative analyses on the feasibility of the proposed ATFCM DCB method considering ATM stakeholders' perspectives.

5 CONCEPTUAL AND MATHEMATICAL MODELLING

5.1 Problem Conceptual Formulation

5.1.1 Characterization of ATM Nodes, Links and Junction Topology

In this thesis, the Air Traffic Management (ATM) airspace operational network is topologically considered as a set of internal fixed nodes (shown as squares in **Figure 37**) and external fixed nodes (shown as circles in **Figure 37**) with directed links among them and link intersections as shown in **Figure 37**. Each internal node ($i, j, \dots$), is simultaneously a sink and source point of traffic flow. It represents the physical volume of airspace occupied by a Terminal Manoeuvring Area (TMA). The external nodes ($k, l, \dots$) are also considered as sinks and sources of traffic flow; they represent entry and exit points of the airspace under consideration.

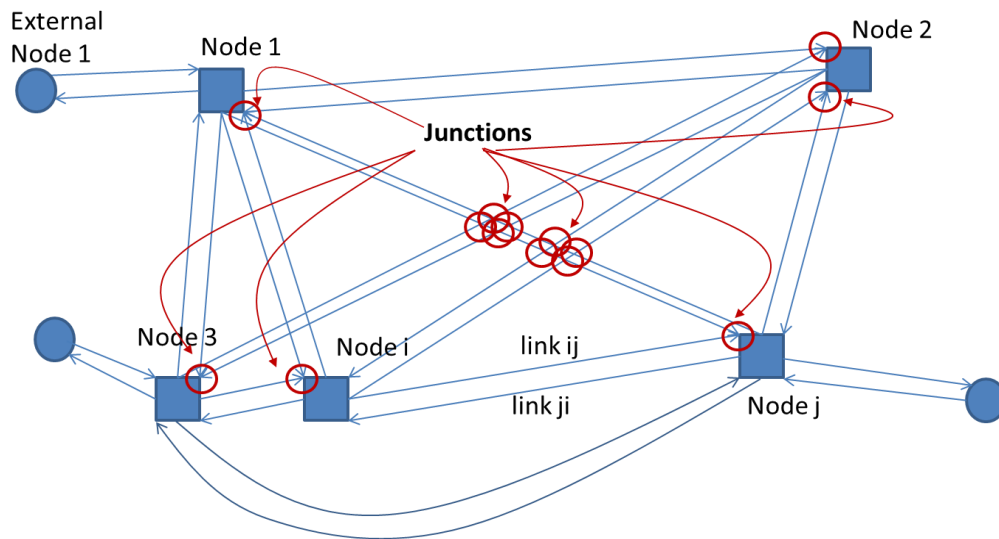


Figure 37: Airspace topology

An internal node (i) shown as a small square in **Figure 37** has outbound traffic to any node (j), represented by exit links (outbound arrows) from i to j , departing from the centre of each square's side. Conversely, the inbound traffic from any node (j) to any node (i) is represented by incoming links (inbound arrows) directed from j to i , entering to each square's corner. The external nodes shown as circles in **Figure 37** also have outbound and inbound traffic.

The links represent planned aircraft trajectory tracks, where the unidimensional continuity principle is applied along them if they do not arrive to any link intersection. An intersection of links is considered as a junction only if it is “active”, that is; when a set of two or more aircraft are expected to arrive to it within a small and well-defined time interval limit which potentially infringe their required safe minimum separation. These junctions may also be defined as locations in the airspace, where two or more links are expected to converge. The active junctions may or may not be co-located with route waypoints (WPs). In this thesis, WPs are understood in two different types: First, as airspace three Dimensional (3D) points where changes on the aircraft velocity vector are expected, and second, as points where a new operational condition is applied to the flight.

Theoretically, the geometry of a junction can be defined by its physical intersection [145]. The junctions could have m incoming links and n outgoing links as shown in **Figure 38**. When $n=m$, the junction is referred to as a crossing point. Whilst, when $m>n$, it is considered as a merging point. The nodes of the current Air Traffic Service (ATS) route network are usually merging points. Finally, when $n>m$, the junction is referred to as a distribution or a fork point. These three geometries characterising a junction represent the three conflict geometries that are considered in this thesis.

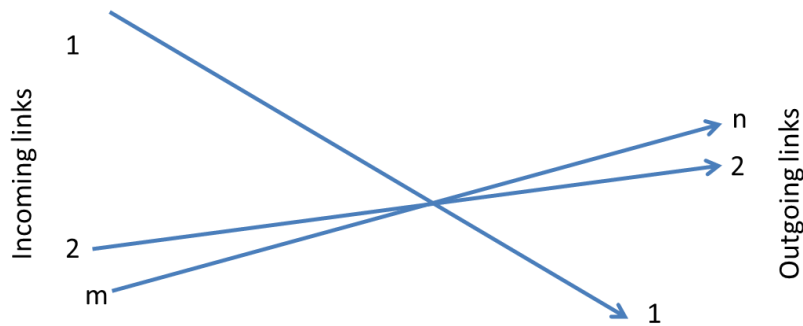


Figure 38: Junction geometries

From the airspace topology defined in **Figure 37**, let assume that all outbound traffic emerging from node (i), denoted as q_{ij} , flows towards all other nodes j . Similarly, all inbound traffic, denoted as q_{ji} , is assumed to flow towards node (i) arriving from all nodes j . Both inbound and outbound traffic must satisfy the inbound limiting throughput

criterion, denoted as QI_i , and the outbound throughput criterion, denoted as QO_i , respectively. Thus, considering all nodes N in the considered airspace network, the following equations can be stated for each node (i):

$$QI_i \geq \sum_{j=1, j \neq i}^{N-1} q_{ji} \quad (5-1)$$

$$QO_i \geq \sum_{j=1, j \neq i}^{N-1} q_{ij}$$

QI_i and QO_i are then the maximum allowed flow values for each node (i). These values are time dependant and assumed to be a priori known.

The above assumption is based on the consideration that the management of the TMA capacities in terms of inbound and outbound maximum flow values (QI_i and QO_i) is sufficiently supported by the Extended Arrival Management (E-AMAN¹⁸) / Departure Manager (DMAN¹⁹), such that QI_i and QO_i are considered as boundary conditions of the problem. In other words, for ATFCM DCB purposes in this thesis, all the capacity information required to meet the criteria in Equation (5-1) for all nodes in the TMA, is provided for. Therefore, all the remaining discussion in this thesis refers to the airspace

¹⁸ The Extended Arrival Management (E-AMAN) concept allows air traffic controllers to meter traffic into a busy Terminal Movement Area (TMA) from far out in the en-route airspace. This is feasible by extending the AMAN's operational horizon from the airspace close to the airport to a horizon further upstream, in adjacent en-route airspace. Typically, an E-AMAN solution is implemented using a SWIM-compliant information exchange infrastructure that delivers AMAN output information (e.g., target times, time to lose/time to gain advisories) to controllers upstream.

¹⁹ The Departure Manager (DMAN) is a planning system to improve departure flows at an airport by calculating the Target Take-Off Time (TTOT) and Target Start-up Approval Time (TSAT) for each flight, taking multiple constraints and preferences into account. Its major objectives are to manage efficiently the departure traffic at an airport, ensuring that the maximum available runway capacity is used, and that additional constraints, such as ATFCM requirements, are properly managed.

beyond the limits of the TMAs' borders, as also previously stated in the thesis main assumptions.

The first equation in Equation (5-1) also applies to active junctions, such that the maximum number of aircraft arriving to any active junction (m) shall be less than or equal to the junction's inbound flow capacity:

$$QI_m \geq \sum_{j=1, j \neq m}^{N-1} q_{jm} \quad (5-2)$$

The capacity limit defined in Equation (5-2) is particularly important at merging points, especially those that are entry points to the nodes where the incoming traffic is confined into higher density outbound routes. For such merging points (junctions), if their capacity limit is not fixed, the required change in aircraft Times of Arrival (TOA) to remove conflicts may increase without bound when the inbound traffic reaches the junction's inbound flow capacity (QI_m). The junction's inbound flow capacity (QI_m) is fixed considering the system uncertainties, as discussed later in Section 5.5.

5.1.2 Conflict and Hotspot Pre-flight Characterisation

Hotspot identification is defined as a process of identifying groups of closely spaced aircraft arriving at a junction. A "hotspot" is a spatiotemporal entity where a set of aircraft is involved in conflicts; with their TOAs at a junction relatively close such that they are violating a pre-determined required safe time separation among any pair of them.

Hotspot characterisation can be performed by either using the traffic complexity metrics [146], or by aggregating the space and time of induced effects (spatiotemporal interdependency) for all pairwise conflicts. In this thesis, the latter criterion is used. To apply this criterion, conflicts are determined based on their TOA separation at junctions, complemented with a spatial indicator regarding the traffic complexity for the conflict's surrounding area.

The above criterion combines Lagrangian and Eulerian views of the problem in a complementary manner. In this context, the Lagrangian knowledge of individual flight trajectories is used to enable tracking the entire trajectory of each aircraft to identify conflicts (TOA separation infringements at junctions), and to enable computing the speed/TOA changes of each aircraft required to remove those identified conflicts. An Eulerian aggregated traffic flow view, on the other hand, is used to enable the formulation of a metric to measure the complexity of the local area surrounding the conflict.

In this thesis, every conflict at any junction is identified at pre-flight phase. The required optimised TOA changes to remove conflicts are also computed at pre-flight phase. The computed TOA changes at junction for each aircraft are achieved through changes in aircraft's speed profile which may induce conflicts at other junctions of other aircraft trajectories. This is referred to as “temporal” impact of the conflict removal. Therefore, the removal of a particular conflict demands an analysis of the whole set of junctions along the whole set of aircraft trajectories in the considered network to take into account this possible temporal impact.

Additionally, at each junction where aircraft's TOAs have been changed, an analysis of complexity in the surrounding traffic (spatial impact) is performed by considering the traffic density and traffic intrinsic complexity, derived from a metric based on the ratios between aircraft's estimated velocities and distances to the junction.

Figure 39 describes the aforementioned twofold views of conflict resolution impact: The view on induced conflicts along trajectories (Lagrangian view), complemented by the view on the complexity of the surrounding area (Eulerian view).

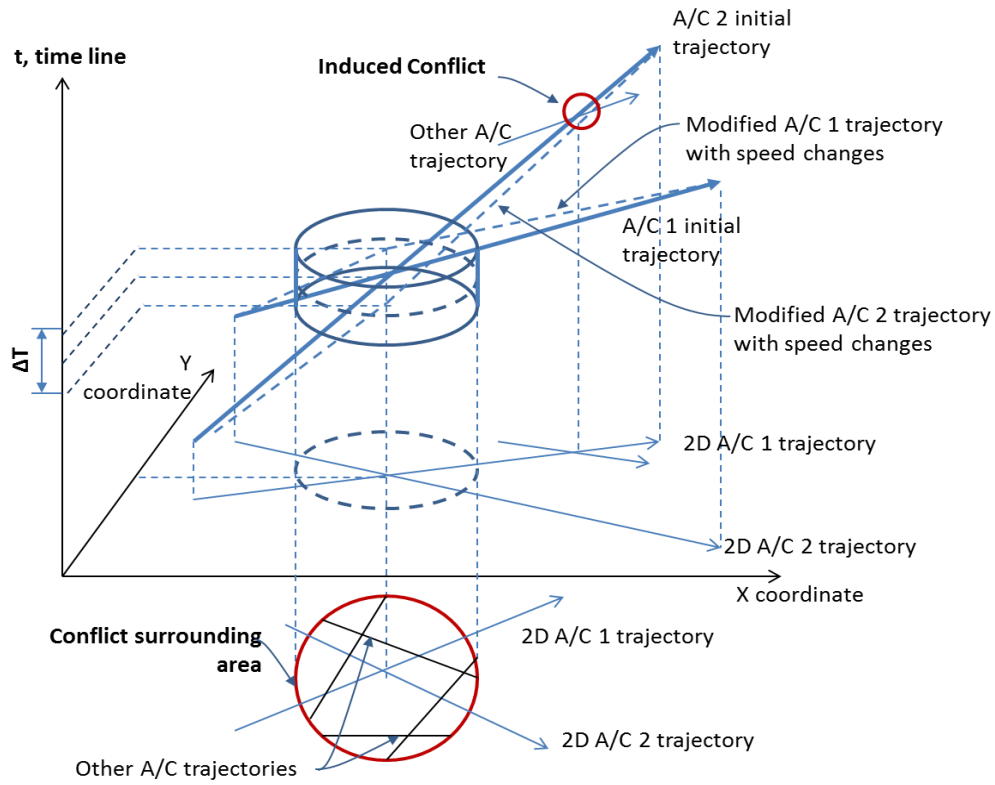


Figure 39: Spatial and temporal impacts of aircraft conflict resolution

Due to the aforementioned spatial and temporal possible impacts of the conflict removal, for each active junction, the following analyses are performed:

1. Determine the spatial impact of the solution: Analyse the complexity of the traffic surrounding an active junction at which speed/TOA changes have been applied.
2. Determine whether there is a temporal impact of the solution. In other words, determine if the applied TOA/Speed changes to remove conflicts at an active junction will induce any other conflicts at subsequent intersected trajectories.

The discussion in this section concerns with the complexity of the traffic surrounding an active junction whereas the discussion on the temporal impact of the solution is provided in Section 5.6. It is necessary to mention that comprehensive modelling of air traffic complexity is beyond the scope of this thesis. The spatial complexity metric developed in this section is only to complement the proposed ATFCM DCB method by identifying some severe hotspot situations where pre-flight aircraft de-confliction by

TOA adjustment may not be possible, thus requiring real-time Air Traffic Control (ATC) interventions. Since any pre-flight/strategic de-confliction is based on aircraft planned trajectories, it cannot ensure a conflict free scenario for actual entire flown trajectories. This can be either due to uncertainties that cannot be captured in pre-flight stochastic characterisation of the system, or due to a particular situation that is beyond the chosen limiting boundaries (outliers) of a pre-flight de-confliction solution.

Under any situations above, the ATC system has to be able to maintain the required safety level through ATCO's reactive interventions. The ATM capability for managing such situations depends on the available resources that can be devoted to cope with these situations at the time of their occurrence, as well as on the complexity of the situation itself. The complexity of the airspace changes in time and location, therefore, it has to be continuously monitored and mitigated. Continuous monitoring of the air traffic complexity helps to identify which player (ATFCM, ATC or AC) is the best actor to act, as well as to determine the best look-ahead time horizon (planning or execution) in which the ATM capabilities should be employed in order to properly react to the situation in the most safe and efficient manner. In this context, a complexity metric can then be used to decide whether a local situation surrounding an active junction can be resolved by pre-flight de-confliction at planning DCB level reducing the ATC tactical interventions as proposed in this thesis, or if the situation does require an ATC and/or aircraft tactical intervention.

The approach to formulate the traffic complexity metric adopted in this thesis is based on previous works by Delahaye and Puechmorel [147][146]. From these two references, two main parameters are adopted and further developed: "Air Traffic Density" and "Intrinsic Complexity".

The purpose of this complexity analysis is to associate a complexity indicator to any active junction in order to quantify the traffic complexity generated by the involved aircraft in the conflict at that junction and the surrounding aircraft. This assessment completes the information required to support an ATFCM DCB planning process. In other words, it helps to determine whether the junction should be declared as a "severe

hotspot” meaning that it has a high complexity and subsequently considered as a situation requiring special ATM attention and resources.

The definition of the aforementioned two parameters is based on the 3dimensional (3D) coordinates of the junction and the “time of interest”. The 3D-coordinates are priori known, and the time of interest (t_{m0}) for any active junction m can be established as the ratio of the mean time of all modified expected TOAs to the active junction for aircraft i , (t_{mi}^+), to the total number of aircraft expected to arrive to that active junction (N_m) such that:

$$t_{m0} = \frac{\sum_i t_{mi}^+}{N_m} \quad (5-3)$$

In Equation (5-3), it is assumed that a finite and small number of aircraft among all the aircraft arriving at junction will be in conflict(s) and that TOA changes are required only for those aircraft.

Once both the junction coordinates and the time of interest (t_{m0}) are known, the traffic density (D_m) and intrinsic complexity (I_m) are then computed for the time of interest t_{m0} . The traffic density is defined as a superficial relative density. This definition changes the formulation proposed in [146] to:

$$D_m = R^2 \sum_{n=1}^N \frac{1}{\max(d_{mn}, R/2)^2} \quad (5-4)$$

The quantity d_{mn} is the distance between the A/C (n)’s position and the junction (m), and R is the characteristic distance used for the definition of the area surrounding the active junction. To avoid singularity in Equation (5-4) when $d_{mn} \rightarrow 0$, the value $R/2$ is used in the equation instead of d_{mn} when $d_{mn} \leq R/2$. The summation in Equation (5-4) considers all A/C (N) within a given distance ratio (for instance, $3R$).

The Intrinsic complexity is based on the air traffic surrounding the active junction at a reference time (t_{m0}), modelled as a local linear dynamical system. The idea of this approach is to model a set of N aircraft trajectories in the vicinity/surrounding area of

the active junction as a flow of traffic evolving like a dynamical system, defined by Equation (5-5):

$$\dot{X} = f(X) \quad (5-5)$$

The quantities $\dot{X}$ and X are the speed and position of the aircraft in the surrounding area of the active junction m located at a point X_m , respectively. Assuming the first spatial derivatives exists, Equation (5-5) can be rewritten as:

$$dX = J_f dX \quad (5-6)$$

In Equation (5-6), J_f represents the Jacobian matrix for the function $f(X)$ at point X_m . For smooth behaviour of $f(X)$, the above equation can be approximated by Equation (5-7):

$$\dot{X} - \dot{X}_m = J_f(X - X_m) + HOT \approx J_f(X - X_m) \quad (5-7)$$

Taking X_m as the origin, Equation (5-7) then becomes:

$$\dot{X} \approx J_f \cdot X + \dot{X}_m \quad (5-8)$$

From Equation (5-8), the variable X represents the aircraft position coordinates in the vicinity of junction m , and $\dot{X}$ represents the speed of the aircraft flow at point X_m . Using the usual notations and terminology of linear dynamical systems in Equation (5-8), $A=J_f$ and $B=\dot{X}_m$. The homogenous part ($A \cdot X$) exhibits the dependence of the aircraft velocity on its position whereas the independent part (B) represents the drift or velocity of aircraft flow at X_m .

The analysis on matrix $\mathbf{A}$ enables the visualisation of the air traffic dynamics with respect to point $\mathbf{X}_m$. The real parts of eigenvalues of matrix $\mathbf{A}$ determine the convergence or divergence properties of the traffic flow at the junction. When the eigenvalue has a positive real part, the flow in the corresponding eigenvector is expanding, whereas when it is negative, the flow is contracting. Furthermore, the imaginary part of the eigenvalues provides information on the curl (vorticity) of the traffic flow dynamics.

The Least Mean Square regression is applied in order to extract the best estimate for matrix $\mathbf{A}$ and vector $\mathbf{B}$. Based on the observations of aircraft positions and speed vectors, the dynamical system model is then adjusted. For each A/C (n) with its position ($\mathbf{X}_n$) and velocity ($\mathbf{V}_n$) given, an error criterion between the system's model and observations can be used to define the cost function (L), as shown in Equation (5-9):

$$L = \sum_{n=1}^N \|\mathbf{V}_n - (\mathbf{A} \cdot \mathbf{X}_n + \mathbf{B})\|^2 \quad (5-9)$$

From Equation (5-9), the matrix $\mathbf{A}$ is determined, and its eigenvalues are determined and used to compute the intrinsic complexity (I_m). The greater the negative real part of the eigenvalues, the higher the degree of traffic flow convergence to the junction becomes, hence, the more complex the traffic situation surrounding the junction. In addition, the greater the imaginary parts of the eigenvalues, the higher the traffic flow vorticity in the junction vicinity will be which also indicates higher complexity of traffic situation surrounding the junction.

When the airspace topology was described in **Figure 37** (see Section 5.1.1), it was assumed that the internal nodes include the whole network airspace within the TMAs, which was considered as a boundary condition. In reality, higher degrees of air traffic vorticity are expected in the airspace within TMAs. Therefore, for the sake of convenience, only the real part of eigenvalues is retained in defining an intrinsic complexity indicator.

The eigenvector of matrix $\mathbf{A}$, enables to determine the “main directions” of where the incoming traffic to the active junction is arriving from by using a characteristic time established by its eigenvalue ($-\frac{1}{real(eig(k))}$ s, in units of time). This characteristic time computed as the opposite of the inverse of the real part of eigenvalue of matrix $\mathbf{A}$, can be seen as the traffic convergence time to the active junction.

When the traffic convergence time is compared to the usual reaction time of the ATC system (T_{ATC}), which is normally between 2 to 6 minutes [148], the resulting ratio ($-\frac{1}{real(eig(k))} = T_{ATC}$) provides a relevant indicator on the ratio between the traffic convergence time and the ATC required reaction time (T_{ATC}). This ratio determines the severity of the traffic situation. When $-T_{ATC} \cdot real(eig(k)) > 1$, the traffic situation in the vicinity of the junction is severe whereas smaller ratios suggest a more relaxed traffic scenario. The proposed intrinsic complexity indicator (I_m) at the junction (m) is defined as an exponential function of the above ratio considering all the 3 real parts of the eigenvalues of matrix $\mathbf{A}(k)$, such that:

$$I_m = \sum_{k=1}^3 e^{-T_{ATC} \cdot real(eig(k))} \quad (5-10)$$

The overall complexity indicator (C_m) for junction m is formulated by multiplying the traffic relative density (D_m) defined in Equation (5-4), and the above intrinsic complexity (I_m). Assuming that the number of aircraft $N \geq 2$, then:

$$C_m = \left[R^2 \sum_{n=1}^N \frac{1}{max(d_{mn}, R/2)^2} \right] \cdot \left[\sum_{k=1}^3 e^{-T_{ATC} \cdot real(eig(k))} \right] \quad (5-11)$$

It is important to establish a complexity threshold to differentiate those active junctions representing “severe hotspots” from those representing “normal” traffic scenarios that could be realistically solved by minor TOA/speed changes at pre-flight phase. To calculate the complexity, assumptions of a characteristic distance defining the area surrounding the active junction of $R = 5NM$ which is equivalent to the conventional

horizontal separation minima and ATC reaction time $T_{ATC} = 2$ minutes are used. Using these values, different complexity thresholds can be established. For instance, the complexity threshold can be considered as equivalent to that used to trigger a “traffic alert” between two aircraft within a typical ATC- Radar Data Processing System–Short Term Conflict Alert (ATC-RDPS-STCA) algorithm [147]. Using the values for the STCA characteristic time and relative distance of the intruder aircraft ($T_{STCA} \approx 90s$ and $d \approx 15NM$) [148], the resulting complexity value from Equation (5-11) is then:

$$C_m = \left[4 + \frac{1}{9}\right] \cdot \left[e^{T_{ATC} \frac{1}{T_{STCA}}}\right] \approx 16$$

Based on the above result, it is considered that any active junction with a complexity higher than ($C_m = 16$) is classified as “a severe hotspot”, which require the conventional ATC and/or aircraft reactive interventions to resolve conflict.

The exponential behaviour of the second term in Equation (5-11) ($\sum_{k=1}^3 e^{-T_{ATC} \cdot real(eig(k))}$) represents the convergence of traffic towards the active junction. This term causes a very fast increase of the C_m value when the characteristic time ($-\frac{1}{real(eig(k))}$) drops below the ATC’s typical reaction time (T_{ATC}). For instance, using the conditions for Traffic Collision Avoidance System (TCAS) Traffic Advisories time ($T_{TCAS} \approx 48 sec$) [65] and a distance between aircraft ($d \approx 5 NM$), the resulting complexity (C_m) increases from 16 to 60, which is almost four times higher than the established threshold determining a severe hotspot. As a comparison, for a situation of TCAS Resolution Advisory (TCAS-RA)²⁰, the complexity value is approximately 246.

This severity identification of a junction helps to identify the situation where subliminal TOA/speed changes applied at pre-flight phase may not be adequate to remove the

²⁰ Airborne Collision Avoidance Systems (ACAS) provides two types of advisories to pilots: Resolution Advisories (RAs) and Traffic Advisories (TAs). These are defined as follows [63]

1. Resolution advisory (RA): An indication given to the flight crew recommending:
 - a) Manoeuvre intended to provide separation from all threats; or
 - b) Manoeuvre restriction intended to maintain existing separation.
2. Traffic advisory (TA): An indication given to the flight crew that a certain intruder is a potential threat

conflict. Furthermore, the C_m value representing the active junction's complexity can also be used as complementary information to decide the best ATM player (ATFCM, ATC or aircraft) to cope with the particular situation of traffic evolving through an active junction.

5.1.3 Pre-flight Conflict Identification and Mitigation by Speed/TOA Changes

The complexity modelling discussed in previous section, provides a complexity metric to obtain information about the characteristics of surrounding area of an active junction. However, this complexity information is only complementary and not the main purpose of this research. It only helps to conceptualise which conflict situations can be realistically considered within the proposed new ATFCM DCB method. The main purpose of this thesis is to develop a method for conflict identification and mitigation at pre-flight ATFCM DCB level. In this method, trajectory incompatibilities are identified before the flight during the time of issuing the RBTs. Incompatibilities are identified based on time interdependency of trajectories at junctions, and are mitigated by incorporating minor adjustments in aircraft's TOAs at active junctions. These TOA adjustments are achieved using minor aircraft speed changes applied to aircraft speed profiles within the Flight Plans (FPLs). It is particularly important that, at ATFCM DCB level, the applied TOA changes should minimise the probability of actual conflicts by providing network scenarios with conflict free FPLs (RBTs).

The required probability of aircraft simultaneous arrival at junction is set as a target to minimise the probability of actual conflicts and reduce the ATC Separation Management (SM) interventions. This probability target together with the modelled total uncertainty in the aircraft FPLs that cause deviations in aircraft TOA at junction, enable to determine the required minimum safe TOA interval between any two consecutive aircraft at junction.

This method can be seen as a Short-Term ATFCM Measure (STAM) which is issued shortly before departure during the pre-flight DCB timeframe by including time constraint specifications into the initial RBTs to remove pro-actively conflicts at any

flown junctions. Removing conflicts at pre-flight phase using minor aircraft TOA adjustments at junctions should enhance the overall traffic management process.

As discussed in Section 3.2, a conflict between any two aircraft can be identified either by computing their expected separation at their Closest Point of Approach (CPA) or by determining their expected time separation at the junction. It was also established in Section 3.2 that when an aircraft follows a predefined flight plan, defined at pre-flight phase, it will usually have significant along-track unpredicted deviations, leading to strong variations on the CPA location and its respective distance. On the contrary, any aircraft that usually has a well-defined 2D or even 3D position, leading to a well-established 2D or 3D junction, will only have uncertainties on their TOA at that junction, whereas the junction's position remains unchanged. It is for this reason, that a minimum safe TOA separation threshold at junction between any two aircraft is used in this thesis to identify conflicts. If the minimum safe TOA separation threshold is expected to be violated at a junction, the involved aircraft's TOAs are adjusted through minor speed changes in their FPLs' speed profiles, in order to increase separation between any pair of them above this safe threshold.

When optimal speed changes are applied to the aircraft nominal flight speed profiles at pre-flight phase, approximately the same percentage of aircraft TOA at that junction is modified. For instance, for an aircraft flying at 400 Kts for a flight distance of 134 NM, if a speed change of 5% to 10% is applied to remove a conflict, the aircraft's TOA at junction will also be modified by 5% to 10%, equivalent to one to two minutes of TOA adjustment for every 20 minutes of aircraft flight time.

This thesis recognises that minor TOA changes applied by speed control could not always be the distinctive technique to solve certain conflict geometries to reduce the ATC workload. Understanding the geometry of a conflict is crucial in determining the most suitable technique to resolve it, especially when considering the safety levels of the aircraft manoeuvre when a particular technique is applied to that conflict geometry. It is then understood that the proposed method in this thesis should not be the only action applied in order to produce a conflict free airspace. Thus, other collaborative and coordinated actions such as adjusting Estimated Take-Off Times (ETOTS) at the

departing airports [149], offsetting some flights from nominal route and allowing multi-agent separation management while the aircraft are in flight should be applied simultaneously with the proposed method to cope with certain conflict geometries, at different stages of the flight plan lifecycle.

For each active junction, the following parameters are relevant to characterise a conflict:

1. The time interval between the aircraft expected TOAs at junction and their associated uncertainties;
2. The aircraft navigation performance within the links;
3. The angle between the aircraft trajectories centerlines at the junction;
4. The expected groundspeed for each aircraft;
5. The expected relative altitude of aircraft before the crossing point.

As established in Section 5.1.1, this thesis only focuses on crossing, merging and fork active junctions. Therefore, different types of conflict geometries have been intentionally left out in this scope and should be dealt with by other techniques. These other geometries, for examples are “trailing” and “opposite” conflicts. For these two parallel conflict geometries, the following axioms apply:

Trailing and opposite conflicts may occur when two aircraft share the same trajectory such that their trajectories overlap. A trailing conflict may occur when the angle (β) between any two aircraft speed vectors is equal to 0, whereas an opposite conflict may occur when $\beta = \pi$.

A trailing conflict may occur only in the following two situations:

1. If aircraft fly the same trajectory, with same airspeed and were not sufficiently initially separated. In this situation, they would always remain in conflict. However, this situation is very unlikely to occur since in normal circumstances, flights cannot be allowed to take-off, if they are not initially sufficiently separated. This situation is therefore, ignored in this thesis.
2. If the leading aircraft (A/C i) is slower than the follower aircraft (A/C j). In this situation, it is assumed that aircraft are well equipped such that the follower

aircraft may safely overtake the leading aircraft; otherwise, tactical ATC interventions may be unavoidable.

Opposite conflicts are ignored in this thesis, because this geometry of conflict cannot be solved by speed/TOA control techniques. It is assumed that the Semi-Circular Rule (SCR) constraints are sufficient to avoid this type of conflicts. This assumption is similarly made for all parallel conflicts.

As discussed in Section 4.4.3, in order to implement the proposed ATFCM DCB method on realistic air traffic scenarios, the conflict removal achieved by speed/TOA control, is treated as an optimisation problem. A time separation between aircraft TOAs at the junction is used to formulate a cost function for conflict removal, which is based on linear programming (LP) model that seeks to minimise the total aircraft's speed/TOA changes required for conflict removal at active junctions. The problem is formulated considering different scopes of the problem as discussed in the subsequent sections of this Chapter.

5.2 Linear Programming Optimisation Problem for Single Pairwise Crossing Junction ($n=2, m=2$)

This section discusses a simple scenario of conflict problem involving only two aircraft and one crossing junction. Derived from the junction's topology defined in **Figure 38**, a single pairwise crossing junction is where $n = 2$ and $m = 2$. The problem is described by a simple LP optimisation problem that minimises the total aircraft speed/TOA changes required for conflict resolution without considering the aircraft TOA uncertainties at junction. In Chapter 6, results of this scenario are discussed and compared to the results obtained from scenarios that consider aircraft TOA uncertainties at junction. This comparison enables the thesis to analyse the effect of aircraft TOA uncertainties on the magnitude of optimal TOA changes required to remove the conflicts at junction.

Figure 40 is used to describe the problem formulated in this section. It pictures the distance (vertical axis) against the time (horizontal axis) evolution of two aircraft ($A/C1$ and $A/C2$) to and from a crossing junction from their initial positions at points A and C ,

respectively. Their initial trajectories are represented by solid lines, connecting their initial positions (points A and C) before the crossing junction to the next waypoints (points B and D) of A/C1 and A/C2 after the crossing junction, respectively.

As shown in **Figure 40**, A/C2 flying from point C is represented as the second aircraft to arrive at the crossing junction. In order to implement the optimal speed changes required to remove the conflict, A/C2 is required to fly below its nominal speed from its initial position C up to the crossing junction, and then flying above its nominal speed from the crossing point to its final waypoint D. A/C1 on the other hand, is required to do the opposite by flying above its nominal speed from its initial position A to the crossing junction, and flying below its nominal speed from the crossing junction to its final waypoint B. The dotted lines show the aircraft trajectories after speed changes are applied. By comparing the aircraft's initial trajectories and their trajectories after speed changes are applied in **Figure 40**, it is necessary to note that the departure time from each aircraft's initial positions and the Targeted Time of Arrival (TTA) at the final waypoint are maintained in this process.

The above approach provides a good platform to formulate the LP cost function to determine optimal speed changes for each aircraft before and after the crossing junction, when subjected to time constraints.

To formulate the problem, the following denotations are used in **Figure 40**: Two digit subscripts are used; the first digit subscript refers to situations before the junction (denoted by 1) and after the junction (denoted by 2). The second digit subscript refers to the involved aircraft where A/C1 is denoted by subscript 1 and A/C2 is denoted by subscript 2. Finally, the prime symbol (') refers to modified variables (speed or time) over the nominal variables (without a prime). From these denotations, the following variables in **Figure 40** are defined as follows:

For *A/C1*:

t_{11} : Nominal flight time to arrive at junction;

t_{11}' : Modified flight time to arrive at junction;

d_{11} : Flight distance from initial waypoint (point “A”) at junction;

d_{21} : Flight distance from the junction to the last waypoint (point “B”).

For *A/C2*:

t_{12} : Nominal flight time to arrive at junction;

t_{12}' : Modified flight time to arrive at junction;

d_{12} : Flight distance from initial waypoint (point “C”) at junction;

d_{22} : Flight distance from the junction to the last waypoint (point “D”).

The following time intervals in **Figure 40** are also defined:

τ_0 : Initial time of arrival interval at junction between *A/C1* and *A/C2*;

τ_1 : Time interval in advance relative to the initial time of arrival at junction required for *A/C1* to remove the conflict;

τ_2 : Amount of time delay relative to the initial time of arrival at junction required for *A/C2* to remove the conflict.

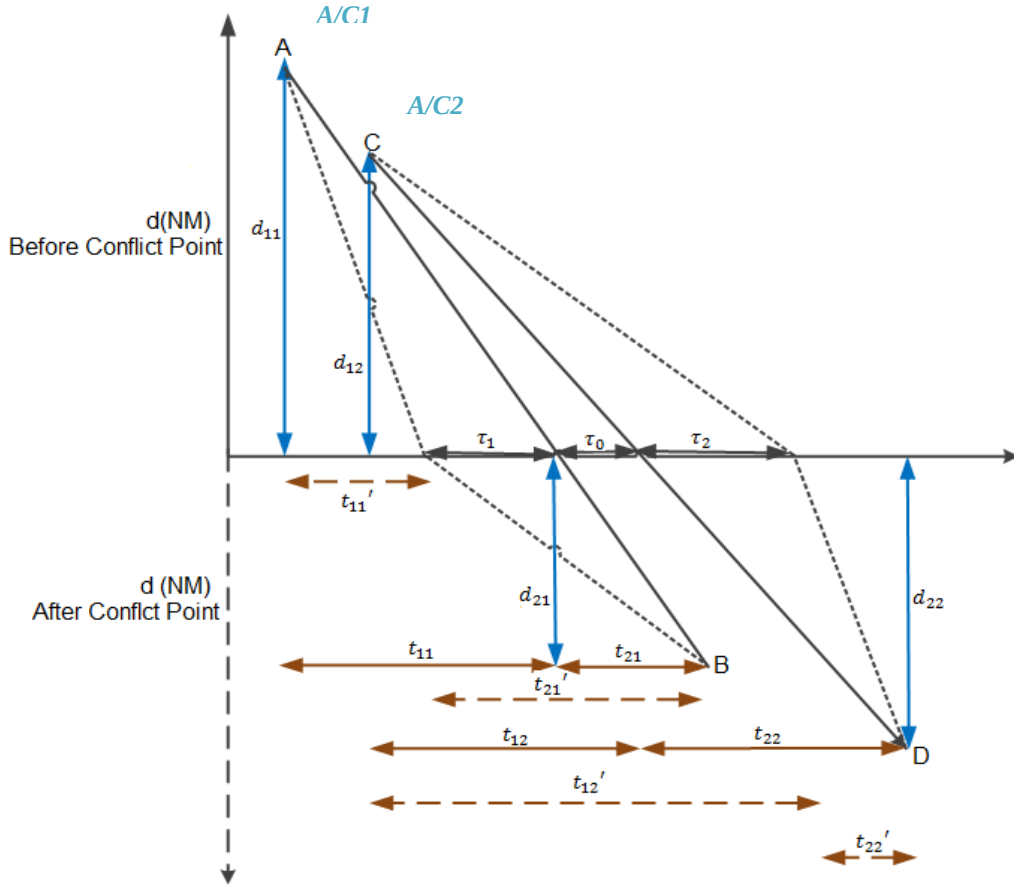


Figure 40: Distance vs. time graph in Lagrangian view of conflict

For each aircraft, constant average speeds are assumed for both nominal and modified speeds. For A/C1, let the nominal and modified speed be denoted as V_{11} and V_{11}' , respectively. From **Figure 40**, these speeds can be expressed as:

$$V_{11} = \frac{d_{11}}{t_{11}}; V_{11}' = \frac{d_{11}}{t_{11}'}$$

The speed change can then be expressed as:

$$\begin{aligned} \Delta V_{11} &= d_{11} \left(\frac{1}{t_{11}'} - \frac{1}{t_{11}} \right) \approx \frac{\tau_1 d_{11}}{t_{11}^2} \\ \Delta V_{11} &= V_{11} \frac{\tau_1}{t_{11}} \end{aligned} \quad (5-12)$$

Let r_{11} be the ratio of the time change at junction for $A/C1$, defined as:

$$r_{11} = \frac{\tau_1}{t_{11}}$$

This time ratio can also be written as a relative speed change, such that:

$$r_{11} = \frac{\Delta V_{11}}{V_{11}} = \frac{\tau_1}{t_{11}} \quad (5-13)$$

From **Figure 40**, the speed change for $A/C2$ can be similarly derived:

$$\begin{aligned} V_{12} &= \frac{d_{12}}{t_{12}}; V_{12}' = \frac{d_{12}}{t_{12}'} \\ \Delta V_{12} &= d_{12} \left(\frac{1}{t_{12}'} - \frac{1}{t_{12}} \right) \approx -\frac{\tau_2 d_{12}}{t_{12}^2} \\ \Delta V_{12} &= -V_{12} \frac{\tau_2}{t_{12}} \end{aligned} \quad (5-14)$$

The ratio of time or speed change for $A/C2$ (r_{12}) is then given by:

$$r_{12} = -\frac{\Delta V_{12}}{V_{12}} = \frac{\tau_2}{t_{12}} \quad (5-15)$$

Following the similar processes above, the required speed changes and the ratios of time or speed changes for $A/C1$ and $A/C2$ after crossing the junction can be obtained by:

For $A/C1$:

$$\begin{aligned} \Delta V_{21} &= -V_{21} \frac{\tau_1}{t_{21}} \\ r_{21} &= -\frac{\Delta V_{21}}{V_{21}} = \frac{\tau_1}{t_{21}} \end{aligned} \quad (5-16)$$

For A/C2:

$$\begin{aligned}\Delta V_{22} &= V_{22} \frac{\tau_2}{t_{22}} \\ r_{22} &= \frac{\Delta V_{22}}{V_{22}} = \frac{\tau_2}{t_{22}}\end{aligned}\tag{5-17}$$

The postulated objective function to be minimised, is formulated as the aggregation of “ratios of time change” of both aircraft, weighted by their flight distances, and is written as:

$$J = [r_{11}d_{11} + r_{12}d_{12} + r_{21}d_{21} + r_{22}d_{22}]\tag{5-18}$$

The objective function in Equation (5-18) is subject to time and speed constraints in Equations (5-19) to (5-22) stated as follows:

To achieve the additional required time separation (τ) at junction, that removes the potential conflict:

$$\tau_1 + \tau_2 = \tau\tag{5-19}$$

To limit the maximum allowed speed changes at values bellow a maximum speed change threshold $X\%$:

$$r_{11}, r_{12}, r_{21}, r_{22} \leq 0.0X\tag{5-20}$$

To maintain the initial (planned) aircraft total flight time:

For A/C1:

$$\frac{d_{11}}{(1 + r_{11})V_1} + \frac{d_{21}}{(1 - r_{21})V_1} = t_{11} + t_{21} \rightarrow t_{21}r_{11} - t_{11}r_{21} = 0\tag{5-21}$$

Similarly for A/C2:

$$t_{22}r_{12} - t_{12}r_{22} = 0 \quad (5-22)$$

All the parameters required in the above optimisation model are known except the minimum required time separation between the two aircraft at the junction ($\tau_p = \tau + \tau_0$). This parameter depends on the uncertainties of aircraft TOA at junction, which are modelled and described in the next section.

5.3 Strategic Modelling of Aircraft TOA Uncertainties at Junction

The aforementioned minimum required “safe” time separation (τ_p) between aircraft at junction, defined at strategic level, depends on the degree of adherence of the aircraft actual trajectory to the planned trajectory. EUROCONTROL defines the planned trajectory as the most likely behaviour of a flight through an area of interest over medium and long term planning horizons [21]. As suggested in this definition, the planned trajectory may then suffer from various sources of uncertainties as it is estimated based on the assumptions of expected aircraft behaviour in flight. This behaviour is affected by meteorological and other operational environment and aircraft capability conditions. These uncertainties are affecting the aircraft planned trajectory in terms of vertical, lateral (cross-track) and longitudinal (along-track) deviations. Additionally, the uncertainties due to initial departure time or scheduling deviations also affect the aircraft TOA at junction.

To model and quantify all of these different deviations, all terms are assumed statistically independent or uncoupled. The following subsections establish the contribution of each of the above deviations on the total aircraft TOA deviations at junction.

5.3.1 Effect of Cross Track Errors

In the Performance Based Navigation (PBN) concept, the lateral or cross-track deviation from aircraft’s nominal trajectory is due to the Total System Error (TSE) as discussed in

Section 2.7.4. The cross-track error causes deviations on the actual junction coordinates (geometrical deviations). To establish the contribution of cross-track error on the aircraft total TOA deviations at junction, **Figure 41** is used to represent these geometrical deviations. The picture shows an example of two aircraft; A/Cj and A/Ci, where each is assumed to be flying with a straight trajectory.

The solid lines represent the centrelines of the trajectories, whilst the dotted lines represent the lateral deviations of these trajectories. The ideal trajectories for A/Ci and A/Cj can then be expressed by the first and second equations in Equation (5-23), respectively:

$$\begin{aligned} y &= a_i \cdot x + b_i \\ y &= a_j \cdot x + b_j \end{aligned} \tag{5-23}$$

Given that the two aircraft have the same coordinates at the junction, the coordinates of the junction can be solved such that:

$$\begin{aligned} x &= \frac{b_j - b_i}{a_i - a_j} \\ y &= \frac{a_i b_j - a_j b_i}{a_i - a_j} \end{aligned} \tag{5-24}$$

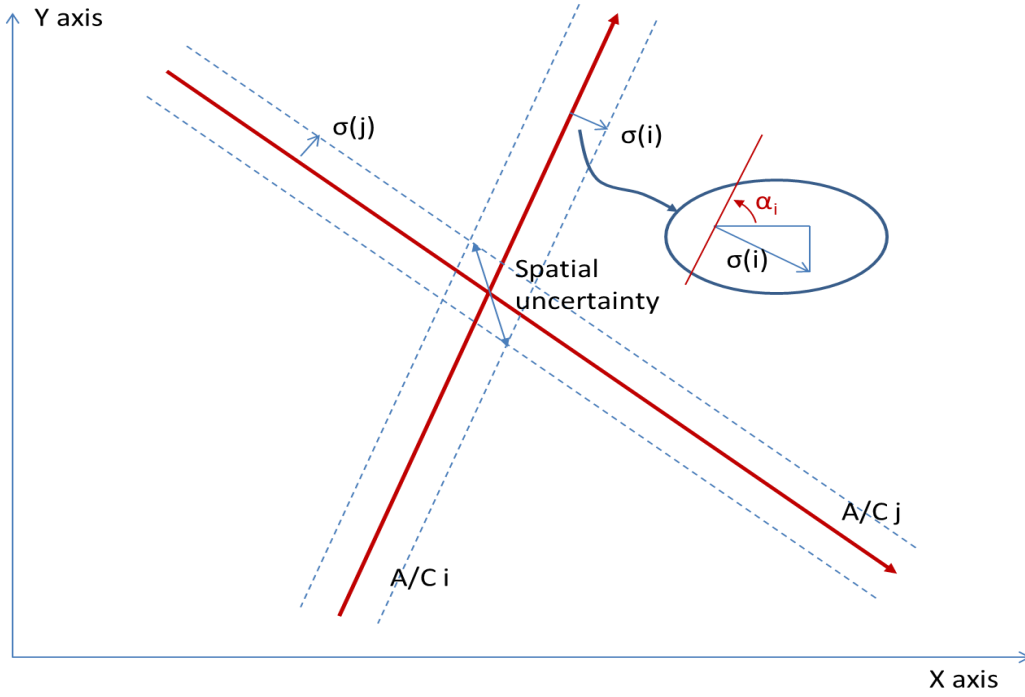


Figure 41: Geometrical uncertainties at junction

From **Figure 41**, assuming both aircraft maintain their headings, it can be seen that the lateral deviations $(\delta x, \delta y)$ of the junction are subject to change by the value of coefficients b_i and b_j of Equation ((5-23), which moves the junction coordinates within an uncertainty area. If the changes of coefficients b_i and b_j are denoted by δb_i and δb_j , respectively, then the junction's deviations due to these variations can be expressed in the following matrix form:

$$\begin{bmatrix} \delta x \\ \delta y \end{bmatrix} = \begin{bmatrix} \frac{-1}{a_i - a_j} & \frac{1}{a_i - a_j} \\ \frac{-a_j}{a_i - a_j} & \frac{a_i}{a_i - a_j} \end{bmatrix} \cdot \begin{bmatrix} \delta b_i \\ \delta b_j \end{bmatrix} \quad (5-25)$$

Based on Equation (5-25), the covariance matrix for the junction coordinates error $(\delta x, \delta y)$ can be derived from the $(\delta b_i, \delta b_j)$ deviations. This is achieved by multiplying the matrix $\begin{bmatrix} \delta x \\ \delta y \end{bmatrix}$ in Equation (5-25) by its transpose matrix $\begin{bmatrix} \delta x & \delta y \end{bmatrix}$, which results in:

$$\begin{bmatrix} \delta x \\ \delta y \end{bmatrix} \cdot \begin{bmatrix} \delta x & \delta y \end{bmatrix} = \begin{bmatrix} \frac{-1}{a_i - a_j} & \frac{1}{a_i - a_j} \\ \frac{-a_j}{a_i - a_j} & \frac{a_i}{a_i - a_j} \end{bmatrix} \cdot \begin{bmatrix} \delta b_i \\ \delta b_j \end{bmatrix} \cdot \begin{bmatrix} \delta b_i & \delta b_j \end{bmatrix} \cdot \begin{bmatrix} \frac{-1}{a_i - a_j} & \frac{-a_j}{a_i - a_j} \\ \frac{1}{a_i - a_j} & \frac{a_i}{a_i - a_j} \end{bmatrix}$$

This then gives:

$$\begin{bmatrix} \delta x^2 & \delta x \delta y \\ \delta x \delta y & \delta y^2 \end{bmatrix} = \frac{1}{(a_i - a_j)^2} \begin{bmatrix} -1 & 1 \\ -a_j & a_i \end{bmatrix} \cdot \begin{bmatrix} \delta b_i^2 & \delta b_i \delta b_j \\ \delta b_i \delta b_j & \delta b_j^2 \end{bmatrix} \cdot \begin{bmatrix} -1 & -a_j \\ 1 & a_i \end{bmatrix} \quad (5-26)$$

The covariance matrix can be defined as the expectation of Equation (5-26), given by:

$$\begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{bmatrix} = \frac{1}{(a_i - a_j)^2} \begin{bmatrix} -1 & 1 \\ -a_j & a_i \end{bmatrix} \cdot \begin{bmatrix} \sigma_{b_i}^2 & 0 \\ 0 & \sigma_{b_j}^2 \end{bmatrix} \cdot \begin{bmatrix} -1 & -a_j \\ 1 & a_i \end{bmatrix} \quad (5-27)$$

Taking the x-axis as coincident with the trajectory of A/Ci such that $a_i = 0$ in Equation (5-27), gives:

$$\sigma_{b_i} = \sigma_{LD_i} \quad (5-28)$$

$$\sigma_{b_j} = \frac{\sigma_{LD_j}}{\cos(\alpha_{ij})} \quad (5-29)$$

where α_{ij} is the crossing angle of the aircraft trajectories.

The variance of the junction position uncertainty is derived from the trace of the covariance matrix defined by Equation (5-27), such that the standard deviation for the position of the junction becomes a function of the standard lateral deviations of aircraft trajectories. These standard lateral deviations are denoted by σ_{LD_i} and σ_{LD_j} for A/Ci and A/Cj, respectively. Assuming both σ_{LD_i} and σ_{LD_j} are equal to a quantity σ_{LD} , then for any crossing angle α_{ij} each aircraft cross-track uncertainty denoted by σ_{CP} can be given as:

$$\sigma_{CP} = \frac{\sigma_{LD}}{\sin(\alpha_{ij})} \sqrt{2} \quad (5-30)$$

Hence, the total cross-track uncertainty of the junction position ($2\sigma_{CP}$) can then be obtained in terms of distance.

From **Figure 41**, the cross-track uncertainty of the junction position, presented by Equation (5-30), can be converted into a time of arrival standard deviation for each aircraft, such that:

$$\sigma_{T1i} = \frac{\sigma_{CP}}{V_i} \quad (5-31)$$

$$\sigma_{T1j} = \frac{\sigma_{CP}}{V_j} \quad (5-32)$$

5.3.2 Vertical Uncertainties

Although this thesis considers flight operations beyond the TMA limits where aircraft are bound to their designated flight levels most of the time, it is still possible to have conflicts evolving in vertical flight. This occurs when a junction involves at least one aircraft crossing the other aircraft's flight level at a 2-dimensional location. It is widely known that the evolution of vertical aircraft position contains a broad range of sources of uncertainty variables, which could be caused by atmospheric states, aircraft performance and other efficiency criteria applied by the AUs and aircraft operators. To simplify this situation of conflicts involving aircraft in vertical flight whilst still fairly maintaining a conservative approach, this thesis assumes that the involved aircraft are considered flying at the same altitude at their time of arrival at the active junction.

5.3.3 Initial Departure Time (Scheduling) Uncertainty

Figure 42 shows the scheduling uncertainties, which are expressed as initial time errors. Let σ_{T2i} and σ_{T2j} be respectively the values of the standard deviation of initial time errors for A/Ci and A/Cj at their flight origin. These values can be directly transformed to the junction with the same values, as shown in **Figure 42**.

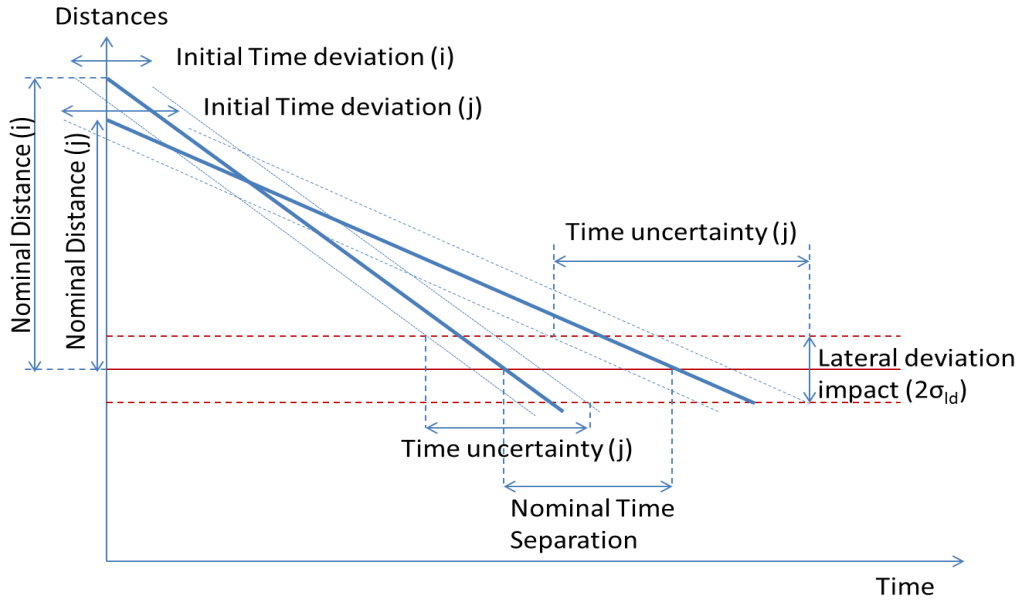


Figure 42: Transformation of initial time deviations to TOA deviations at junction

5.3.4 Along-track Time Uncertainties at Junction

The along-track uncertainty is due to the actual ground speed being different from the expected speed (V_0). This along-track error drifts linearly with time.

In order to derive the impact of a long-track time error on the aircraft TOA at junction, it is first assumed that the aircraft flight distance (d) to the junction is known at pre-flight phase. The expected flight time (t_0) to this junction is then given by:

$$t_0 = \frac{d}{V_0}$$

Any deviation (δV) in the ground speed (V_0) will cause a change in the aircraft TOA at junction, given by:

$$\delta t = -\frac{d \cdot \delta V}{V^2} \approx -\frac{d \cdot \delta V}{V_0^2} \quad (5-33)$$

Equation (5-33) shows that the standard deviation of change in the aircraft TOA at junction (δt), denoted by σ_{T3} in Equation (5-34), is a function of errors in the ground speed with its standard deviation σ_v , which can be written as:

$$\sigma_{3T} = \frac{d}{V_0^2} \cdot \sigma_V \quad (5-34)$$

5.3.5 Summary of Aircraft TOA Deviation at Junction

Section 5.3 has discussed and derived the lateral deviation, the initial time deviation and along-track time deviation for A/Ci and A/Cj trajectories, while transforming these deviations into the deviations of aircraft TOA at junction. The established aircraft TOA at junction standard deviation values associated to each of the above type of uncertainties are summarised in **Table 3**.

Uncertainty at the junction	$A/C\ i, j$ TOA standard deviation
Due to aircraft lateral deviation ($\sigma_{T1i,j}$)	$\sigma_{T1i,j} = \sqrt{2} \cdot \frac{\sigma_{LD}}{V_{i,j} \cdot \sin(\alpha_{ij})}$
Due to Initial time deviation ($\sigma_{T2i,j}$)	$\sigma_{T2i,j}$
Due to a long-track time deviation ($\sigma_{T3i,j}$)	$\sigma_{T3i,j} = \frac{d_{i,j}}{V_{i,j}^2} \cdot \sigma_{Vi,j}$

Table 3: Summary of sources of uncertainties expressed as standard deviations

5.4 Criteria for Minimum Pairwise TOA Separation at Junction

To formulate the required minimum pairwise TOA separation at junction, which is used as the compatibility condition for trajectories of any two consecutive aircraft arriving at junction, the three sources of TOA deviations summarised in **Table 3** are considered statistically independent. Then, by assuming that Gaussian distribution is applied to all of them, the required minimum TOA time interval (τ_p) between any two consecutive aircraft can be derived from a predefined desired probability of aircraft simultaneous arrival (P_c) at junction as discussed below.

From **Table 3**, the total TOA standard deviation at junction for A/Ci and A/Cj can be computed as:

$$\sigma_{Ti,j} = \sqrt{\sigma_{T1i,j}^2 + \sigma_{T2i,j}^2 + \sigma_{T3i,j}^2} \quad (5-35)$$

For any aircraft's time of arrival (t) at junction, the probability of aircraft simultaneous arrival (P_c) at junction can be computed by convolving the probability density function (pdf) associated to A/Ci with the pdf associated to A/Cj , where the pdf for A/Ci and the pdf for A/Cj are respectively given by:

$$f_i(t) = \frac{1}{\sqrt{2\pi\sigma_{Ti}}} e^{-\frac{(t-t_i)^2}{2\sigma_{Ti}^2}}, \text{ and } f_j(t) = \frac{1}{\sqrt{2\pi\sigma_{Tj}}} e^{-\frac{(t-t_j)^2}{2\sigma_{Tj}^2}}$$

The convolution of the above pdfs gives the probability of $A/C i, j$ simultaneous arrival at a junction, given by Equation (5-36) :

$$P_c = \frac{1}{\sqrt{2\pi(\sigma_{Ti}^2 + \sigma_{Tj}^2)}} e^{-\frac{(t_i - t_j)^2}{2(\sigma_{Ti}^2 + \sigma_{Tj}^2)}} = \frac{1}{\sqrt{2\pi(\sigma_{Ti}^2 + \sigma_{Tj}^2)}} e^{-\frac{\tau_p^2}{2(\sigma_{Ti}^2 + \sigma_{Tj}^2)}} \quad (5-36)$$

Then, the required minimum interval (τ_p) between $A/C i, j$'s expected TOAs at junction for a given P_c is:

$$\tau_p = \sqrt{-2(\sigma_{Ti}^2 + \sigma_{Tj}^2) \ln[P_c \cdot \sqrt{2\pi(\sigma_{Ti}^2 + \sigma_{Tj}^2)}]} \quad (5-37)$$

If the expected nominal TOA interval denoted by τ_0 for any two consecutive aircraft at junction is equal or greater than the above-required minimum TOA interval τ_p , there will be no additional time interval required and the aircraft's trajectories will be deemed compatible at junction. Otherwise, a TOA interval increment given by Equation (5-38) shall be required between consecutive aircraft at junction.

$$\tau = \tau_p - \tau_0 \quad (5-38)$$

5.5 Determination of Junction Inbound Capacity with TOA Uncertainties

Based on Equation (5-35), the total standard deviation for A/C i, j 's expected TOAs at junction can be determined as :

$$\sigma_{Total} = (\sqrt{\sigma_{Ti}^2 + \sigma_{Tj}^2})$$

Figure 43 shows the required minimum TOA interval (τ_p) computed for different global σ_{Total} values and different probabilities of aircraft simultaneous arrival at junction values (P_C values). By assuming a constant required minimum TOA interval (τ_p) between any two consecutive aircraft, the maximum inbound flow at the junction (the frequency of traffic) denoted as QI_m can be computed as:

$$QI_m = 1/\tau_p \quad (5-39)$$

It can then be derived from **Figure 43**, that in order to achieve a probability of aircraft simultaneous arrival at junction P_C value below 10^{-3} and a junction capacity of approximately 6 aircraft per hour, a total TOA standard deviation of ≤ 3 minutes will be required. This quantitatively indicates a strong sensibility of the required minimum TOA interval at junction to the aircraft TOA uncertainties at junction. This also shows that the proposed pre-flight changes of aircraft TOAs at junction to remove conflicts, allow an inbound traffic flow at junction of up to 6 aircraft per hour, only when the actual total aircraft's TOA at junction uncertainty is reduced below a total TOA standard deviation of 3 minutes. However, as discussed below, a total TOA standard deviation value ≤ 3 minutes can only be achieved under specific operational and aircraft capabilities conditions.

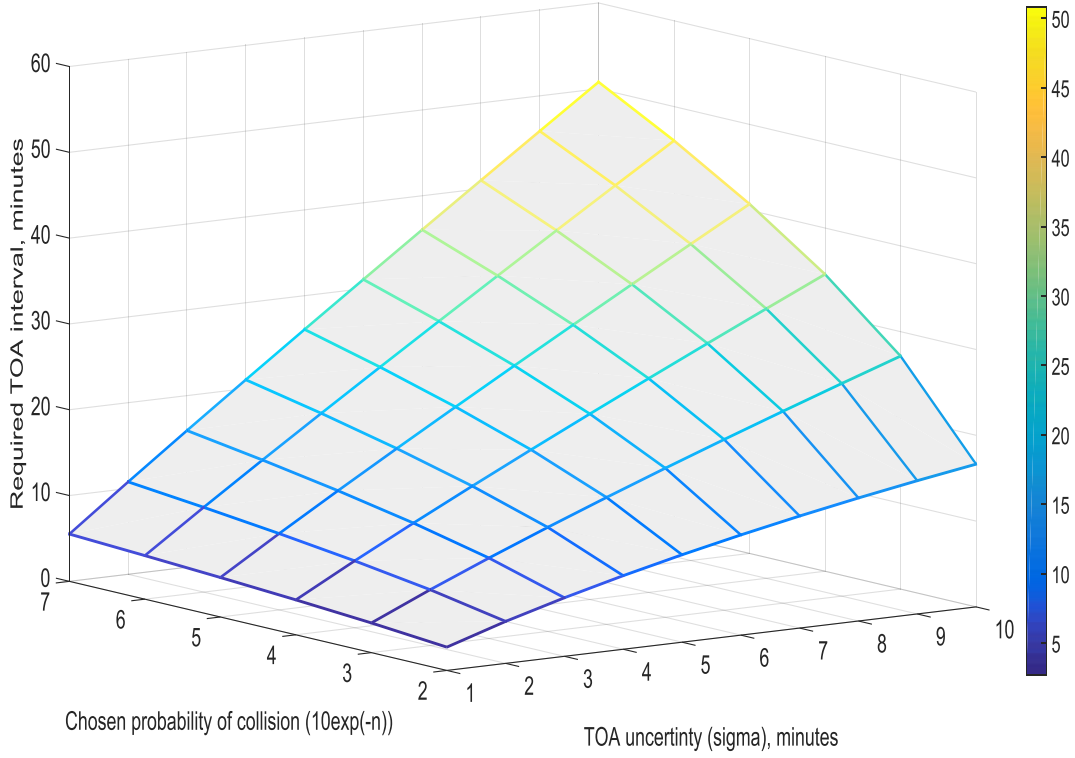


Figure 43: Required minimum TOA interval for different probabilities of aircraft simultaneous arrival at junction and different aircraft total TOA standard deviations

Uncertainties due to lateral deviations, which have been defined in terms of TOA standard deviation expressed as $\sigma_{T1i,j} = \sqrt{2} \cdot \frac{\sigma_{LD}}{V_{i,j} \cdot \sin(\alpha_{ij})}$ in **Table 3**, depends on the navigation performance accuracy (σ_{LD}) that depends on the Required Navigation Performance (RNP) value, aircraft ground speed ($V_{i,j}$) and the crossing angle between aircraft trajectories/tracks at junction (α_{ij}). This dependency is shown in **Figure 44**, where it can be observed that for aircraft crossing angles $\alpha_{ij} \leq 20^\circ$ and speeds $V_{i,j} \leq 200$ Kts the resulting relative TOA standard deviation is:

$$\frac{\sigma_{T1i,j}}{\sigma_{LD}} \geq 1 \text{ minutes/NM}$$

Therefore, by assuming that air traffic is consisted of typical commercial aircraft which usually flies with a speed greater than 200 Kts in en-route airspace, and by assuming crossing angles between tracks greater than 20° , then the relative TOA standard deviation can be reduced to: $\sigma_{T1i,j}/\sigma_{LD} < 1 \text{ minutes/NM}$.

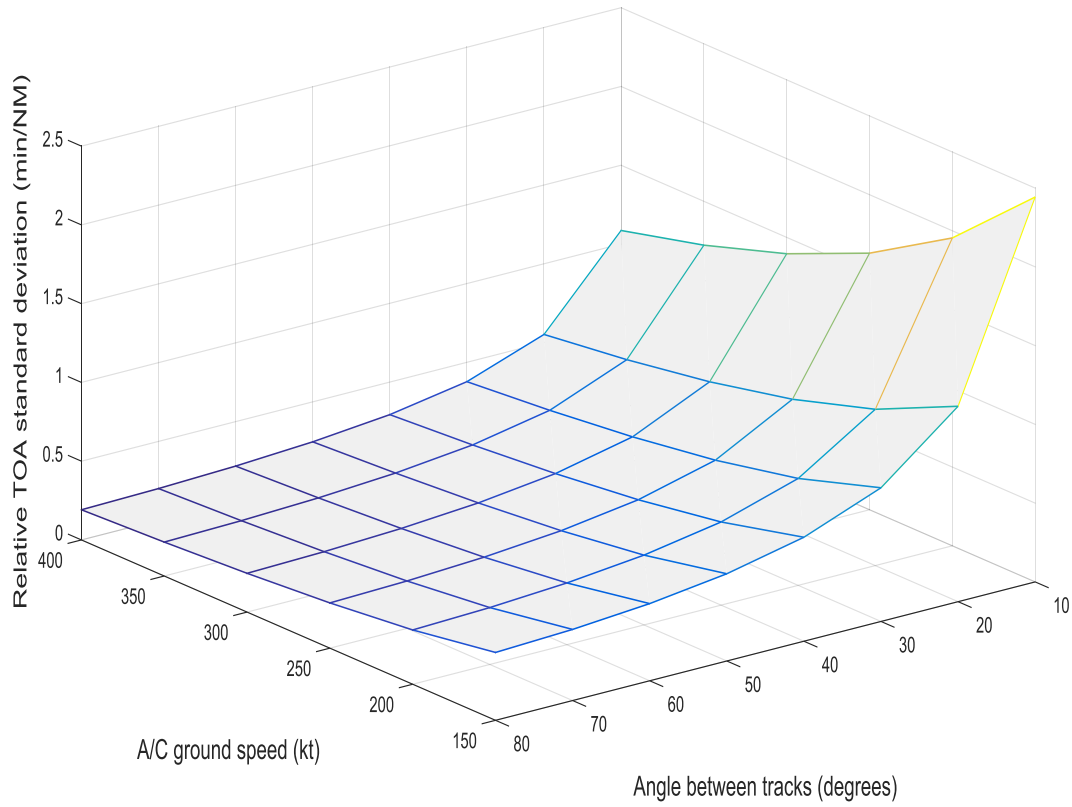


Figure 44: Relative TOA standard deviation at junction vs. aircraft speed and crossing angle between trajectories

The accuracy criterion for RNP-X involves a standard deviation value of $\sigma_{LD} = X/2$. This means that when an aircraft is flying under PBN with RNP-X procedures, the associated standard deviation is $(X/2)$. By considering RNP 1 procedures as earlier assumed in Section 4.3, then the standard deviation $\sigma_{LD} = 0.5 \text{ NM}$. This Results in a lateral TOA standard deviation of $\sigma_{T1i,j} < \frac{\sigma_{LD1min}}{NM} = 30 \text{ seconds}$, which is the value used in this thesis.

Concerning the initial time/scheduling deviations given in terms of TOA standard deviation, denoted by the variable $\sigma_{T2i,j}$ in **Table 3**, this variable is hardly a-priori quantifiable. This is especially due to the limited runway capacities constraining departures, and the various uncertainties that dynamically affect runway capacity. According to the EUROCONTROL Performance Review Report (PRR) [150], 0.9 minutes per departure due to local ATC departure delays at the gate and 3.5 minutes

delay per departure due to additional taxi-out time were registered at the top 30 busy airports in Europe in 2016.

In this thesis, it is considered that the above delays can be reduced by applying new operational concepts such as Airport-Collaboration Decision Making (A-CDM) at the airport to synchronise activities of all concerned ATM agents at each airport in European Civil Aviation Conference (ECAC) area to maximise the departure predictability [151]. In addition, other ongoing research projects such as the User Driven Prioritisation Process (UDPP) [151], seeks to significantly reduce the level of the departure inefficiency to a target of ≤ 30 seconds departure delay on average per flight. By relaxing the above target, an initial/scheduling time standard deviation of 1 minute ($\sigma_{T2i,j} = \pm 1$ minute) is considered realistically achievable in the future, and assumed in this thesis.

The last source of uncertainty considered is the along-track deviation expressed in **Table 3** as $\sigma_{T3i,j} = \frac{d_{i,j}}{V_{i,j}^2} \cdot \sigma_{Vi,j}$, this variable depends on the aircraft ground speed errors ($\sigma_{Vi,j}$), the flight distance to the junction ($d_{i,j}$) and the aircraft ground speed ($V_{i,j}$). In the literature, 12 Kts has been often used as a typical standard deviation of ground speed errors [152]. Using this value, the impact of aircraft nominal ground speed ($V_{i,j}$) and the impact of flight distance to junction ($d_{i,j}$) on the along-track deviation ($\sigma_{T3i,j}$) is computed and shown in **Figure 45**.

As shown in **Figure 45**, when the flight distance to the junction is above 500 NM, the along-track standard deviation grows above 2 minutes for aircraft speeds below 400 Kts. This clearly shows that with 12 Kts standard deviation of ground speed errors and flight distances to the junction that are above 500 NM, the along-track deviations could reach unacceptably high level of uncertainty for practical FPLs. Such high along-track uncertainties also require reducing the junction's "safe" capacity below a reasonable operational level. To overcome these challenges, it is assumed that the aircraft are equipped with an on-board Controlled Time of Arrival (CTA) functionality, which has an accuracy of ± 30 seconds. However, even by relaxing the above CTA accuracy from

$\sigma_{T3i,j} = \pm 30$ seconds to $\sigma_{T3i,j} = \pm 1$ minute, acceptable results can be achieved in this thesis.

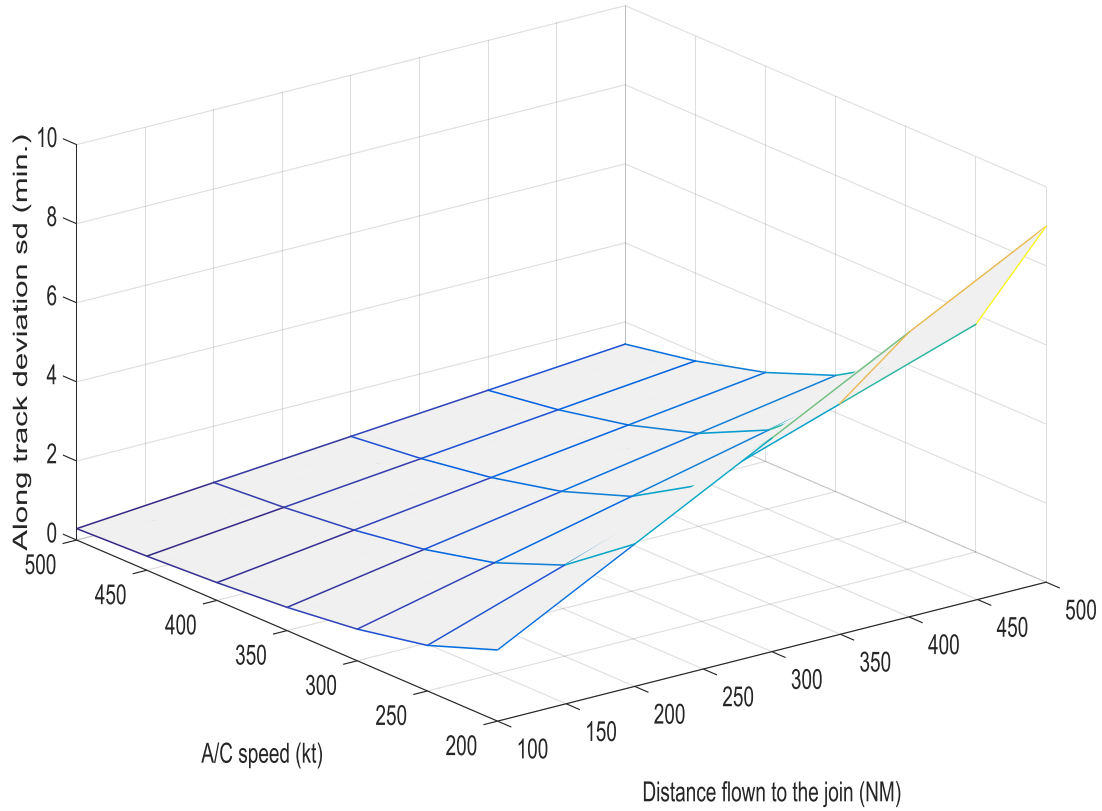


Figure 45: Along-track standard deviation vs. aircraft speed and flight distance to the junction at 12 Kts of ground speed uncertainty standard deviation

In summary, this section has shown how a junction's inbound flow capacity strongly depends on aircraft's TOA uncertainties at junction (see **Figure 43**). It has been established that only when the level of TOA uncertainties at junction is ≤ 3 minutes, the expected junction's flow capacity remains high enough to support the proposed application of pre-flight changes on the aircraft TOAs at junctions for conflict removal. In order to achieve realistic TOA standard deviation values, specific operational and capability conditions have been proposed and assumed.

Table 4 summarises the adopted values of TOA standard deviations at junction and the operational and aircraft capability conditions assumed for each type of uncertainty.

Type of uncertainty	Resulting TOA standard deviation	Required conditions assumed
aircraft lateral deviation	$\sigma_{T1i,j} = 30s$	Crossing angle $\alpha \geq 20^0$ and RNP1
Initial time deviation	$\sigma_{T2i,j} = 1min$	SESAR Projects' Targets
Along-track time deviation	$\sigma_{T3i,j} = 1min$	Aircraft are CTA equipped
Total combined time deviation	$\sigma_T = 1.5min$	All of the above

Table 4: Summary of assumed required TOA standard deviations

Considering the above values and using the total TOA standard deviation obtained in **Table 4** ($\sigma_T = 1.5$ min), the required minimum TOA interval (τ_p) is computed from Equation (5-37) for different probabilities of aircraft simultaneous arrival at junction (P_c). The results are presented in **Figure 46**. As shown in **Figure 46** for instance, to achieve a probability of aircraft simultaneous arrival at junction value of $P_c = 10^{-5}$, a minimum TOA separation interval between any two consecutive aircraft of approximately $\tau_p = 9.4$ minutes is required. This implies permitting a maximum junction's inbound traffic flow capacity ($QI_m = \frac{1}{\tau_p} hr$) of 6 aircraft per hour. Such a low probability should result in a low conflict risk among any en-route air traffic scenario. Therefore, it should significantly reduce the current ATC tactical interventions required to resolve conflicts, hence decreasing their overall workload. However, even higher probabilities of simultaneous arrival at junction (P_c) values can remove conflicts and reduce the current ATC workload as discussed later in Chapter 7.

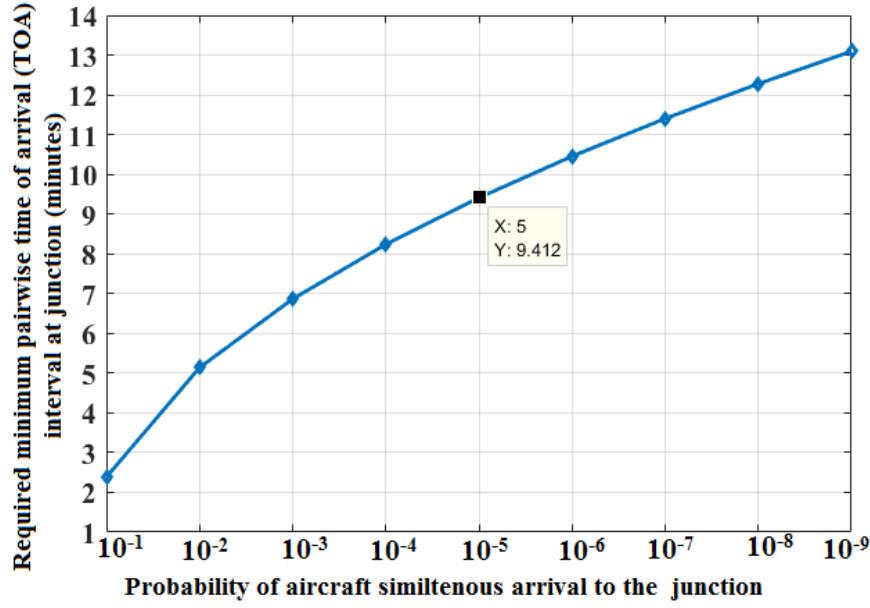


Figure 46: Required minimum pairwise TOA interval at junction for different probabilities of aircraft simultaneous arrival at junction.

5.6 A Linear Programming Optimisation Problem Considering Crossing, Merging and Multiple Junctions along Trajectories

In section 5.2, the developed LP optimisation model considered a pairwise separation problem at a single crossing junction, without considering the effect of aircraft TOA uncertainties at junction. In this section, the scope of the problem is extended to include also situations of merging conflicts and situations where an aircraft may have multiple conflicted (active) junctions along its trajectory. The formulation of this problem also considers the required minimum TOA separation at junction determined by the total trajectory uncertainty and the required P_C value as derived in Section 5.5.

Any link, which represents a planned trajectory (i) of A/C_i (See Section 5.1.1), can have different active junctions where TOA changes are required. In addition, it may be necessary to apply TOA changes to more than two aircraft at the same junction (merging conflict) in order to resolve all conflicts at that junction. **Figure 47** shows the distance/time evolution graph for A/C_i which has two consecutive active junctions “junction m ” and “junction ($m + 1$)” where changes in the expected TOAs at both of these junctions are required for A/C_i and A/C_j at junction m (crossing junction), and for A/C_i , A/C_k and A/C_l at junction $m + 1$ (merging junction).

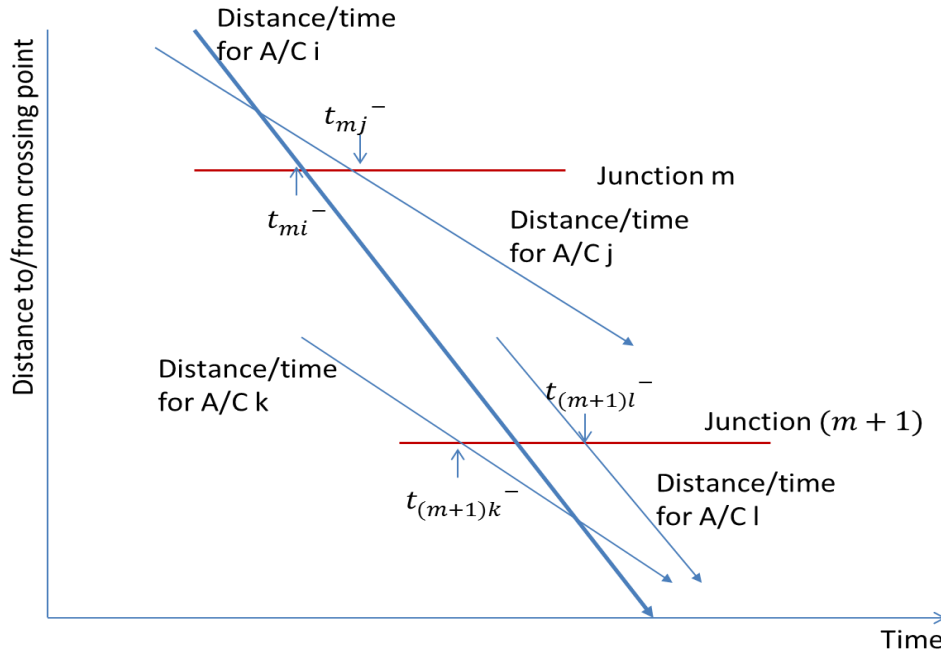


Figure 47: Distance/time evolution for A/Ci, having conflicts at crossing junction m and merging junction $m + 1$

To solve conflict situations such as that illustrated in **Figure 47**, optimal changes in aircraft TOA at junctions for all involved aircraft that removes all conflicts at all active junctions to achieve a P_c value required to reduce ATC SM tactical interventions are computed. These speed/TOAs changes are computed using a novel Linear Programming (LP) optimisation model, which minimise the total amount of distance-weighted speed changes. Within the proposed ATFCM DCB method, it is postulated that these speed/TOA changes shall be issued by the NM through including them within the RBTs in a form of requested Targeted Time of Overfly (TTOs) for en-route junctions and TTAs to junctions in TMAs entry points. Before formulating the proposed LP optimisation model, its unique four main constraints are established as follows:

1. The global time performance at each active junction shall be maintained to keep the entropy of the traffic in the route network and to minimise the disruption of the ATCOs' situation awareness;
2. The minimum TOA interval (τ_p) required to achieve the desired probability of aircraft simultaneous arrival at junction (P_c) value established by Equation (5-37), shall be achieved for any two consecutive aircraft at any active junction;

3. The departure time and the Targeted Time of Arrival (TTA) at final destination shall be maintained for each aircraft;
4. The maximum allowable speed change shall be fixed below a given threshold.

To maintain the global time performance (constraint 1 above), a set of computed new TOAs (t_{mi}^+) at each junction (m), shall have mean time (t_{m0}) same as that of the set of TOAs before applying speed changes (t_{mi}^-), such that:

$$t_{m0} = \frac{\sum_i t_{mi}^-}{N_m} = \frac{\sum_i t_{mi}^+}{N_m} \quad (5-40)$$

Then for all aircraft and all active junctions:

$$t_{m1}^+ + t_{m2}^+ \dots t_{mn}^+ = n \cdot t_{m0} \text{ (Closure condition)} \quad (5-41)$$

The closure condition in (5-41), assumes that the average traffic flowing at junction is low enough to allow finite TOA changes (t_{mi}^+).

To compute the new TOAs at each junction that respects the minimum required TOA interval between any two consecutive aircraft at each junction (constraint 2 above), a set of equations which forms Equation (5-42) referred to as the “junction equation” are used. In this junction equation, each aircraft is assigned a subscript with the number of the order it arrives at junction ($1, 2 \dots n$). For instance, the minimum required TOA interval between any two consecutive aircraft; let say, A/Cp and A/Cq where A/Cq is the first aircraft to arrive at junction m is denoted by τ_{mpq} and can be computed from Equations (5-37) and (5-38).

$$\begin{aligned} t_{m2}^+ - t_{m1}^+ &= \tau_{m21} \\ t_{m3}^+ - t_{m2}^+ &= \tau_{m32} \\ t_{mn}^+ - t_{m(n-1)}^+ &= \tau_{m(n-1)n} \end{aligned} \quad (5-42)$$

The above equations in the junction equation provide the new TOAs for each A/C (i) at each junction (m). These equations have to be solved for all active junctions in the network.

To respect the third of the aforementioned four constraints of the developed LP model, the total flight time shall be maintained such that for the last junction (k) of each flight (i), the initial planned TTA is maintained. Therefore, for all A/C (i), the following condition applies:

$$t_{ki}^+ = t_{ki}^- \quad (5-43)$$

Furthermore, to achieve the last of the aforementioned four constraints, relative speed changes (δV_{im}^{m+1}) between junction (m) and junction ($m+1$) for each aircraft shall be below a given maximum threshold (X %):

$$\delta V_{im}^{m+1} \leq 0.0X \cdot V_{im}^{m+1} \quad (5-44)$$

Once all new TOAs (t_{mi}^+) have been computed for each junction (m) and for each involved A/C (i), while also maintaining each aircraft's departure time and TTA at destination as illustrated in **Figure 48**, then, the required speed changes can be established. **Figure 48** shows the nominal distance/time evolution links for A/C i (in blue colour) and the disturbed/perturbed²¹ distance/time evolution links for A/C i (in red colour). To formulate the required speed changes, the following variables and a constant are first defined:

V_m^{m+1} : Aircraft speed between junctions m and $m + 1$;

d_m^{m+1} : Aircraft distance between junctions m and $m + 1$ (constant);

Δt_m^{m+1} : Aircraft flight time between junctions m and $m + 1$.

²¹ Links assuming TOA changes have been applied

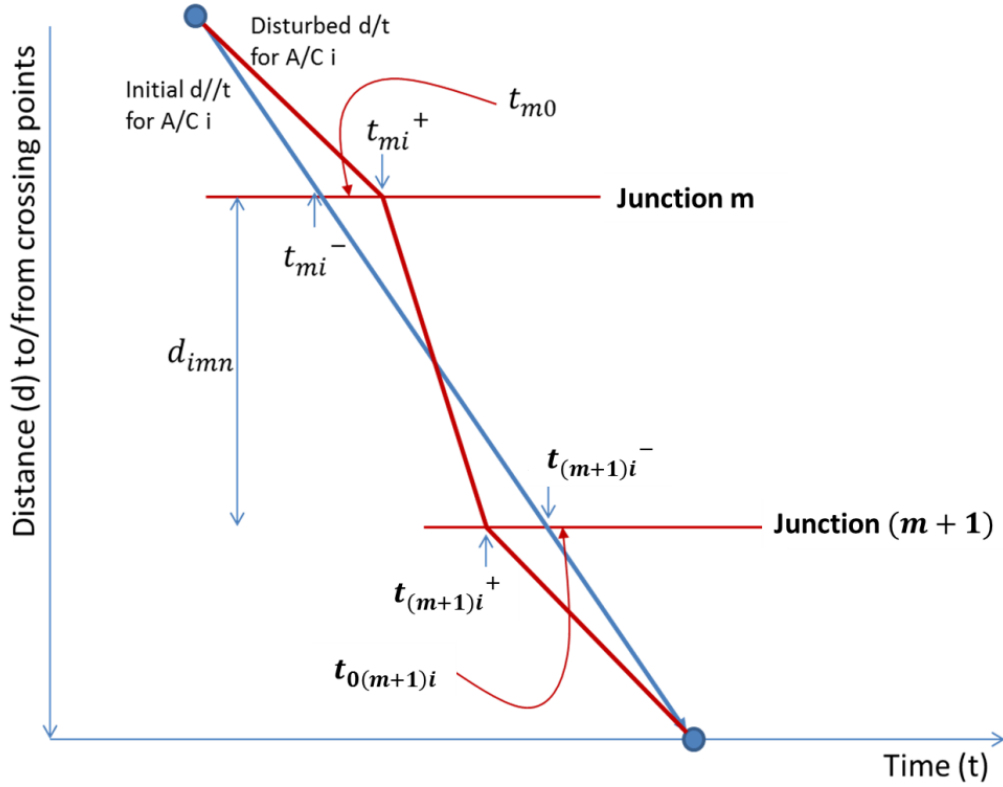


Figure 48: Nominal and perturbed distance/time evolution of A/Ci

The above defined variables and constant are inter-related by the following equation:

$$V_m^{m+1} = \frac{d_m^{m+1}}{\Delta t_m^{m+1}}$$

The relationship between the variations on the aircraft speed between junctions (δV_m^{m+1}) and the variations on the aircraft flight time ($\delta \Delta t_m^{m+1}$) is given by:

$$\delta V_m^{m+1} = -\frac{d_m^{m+1}}{(\Delta t_m^{m+1})^2} \delta(\Delta t_m^{m+1})$$

The variations on the aircraft flight time ($\delta(\Delta t_m^n)$) are known and given by:

$$\delta(\Delta t_m^{m+1}) = (t_{m+1}^+ - t_{m+1}^-) - (t_m^+ - t_m^-)$$

It then follows that:

$$\delta V_{im}^{m+1} = -\frac{d_{im}^{m+1}}{(\Delta t_{im}^{m+1})^2} [(t_{i(m+1)}^+ - t_{i(m+1)}^-) - (t_{im}^+ - t_{im}^-)] \quad (5-45)$$

By applying Equation (5-45) to all aircraft trajectories (i) that have one or multiple active junctions, the speed changes (δV_m^{m+1}) required for all involved aircraft to remove conflicts in the traffic network can be computed. However, when the closure condition in Equation (5-41) was imposed, the limitation on the amount of the required speed changes for each aircraft to remove conflict was ignored, which may lead to unrealistic solutions. To overcome this risk, the closure condition is removed and replaced by a linear optimisation problem where the cost function represents the global required speed changes for all the involved aircraft. From Equation (5-45), the speed change required for any A/C (i) on the trajectory segment (m to $m + 1$) can be expressed as a function of the required time of arrival changes at both junction (m) and junction ($m+1$), such that:

$$\delta V_{im}^{m+1} = -\frac{d_{im}^{m+1}}{(\Delta t_{im}^{m+1})^2} [\tau_{i(m+1)} - \tau_{im}]$$

where:

$$\begin{aligned}\tau_{i(m+1)} &= (t^+_{i(m+1)} - t^-_{i(m+1)}) \\ \tau_{im} &= (t^+_{im} - t^-_{im})\end{aligned}$$

Considering that the flight efficiency of the involved aircraft will be affected by the distance along which the speed change is applied, then, the “cost” for a particular perturbed trajectory can be modelled as $\delta V_{im}^{m+1} \times d_{im}^{m+1}$, which leads to a global cost function obtained as a sum of these elementary contributions given by:

$$\begin{aligned}J &= \sum_i \sum_m \delta V_{im}^{m+1} \cdot d_{im}^{m+1} = - \sum_i \sum_m \left[\frac{d_{im}^{m+1}}{\Delta t_{im}^{m+1}} \right]^2 [\tau_{i(m+1)} - \tau_{im}] \quad (5-46) \\ &= - \sum_i \sum_m [V_{im}^{m+1}]^2 [\tau_{i(m+1)} - \tau_{im}] = \\ &= - \sum_i \sum_m [V_{im}^{m+1}]^2 [(t^+_{i(m+1)} - t^-_{i(m+1)}) - (t^+_{im} - t^-_{im})]\end{aligned}$$

This cost function is subject to the following constraints:

At each junction, the n number of arriving aircraft shall:

1. Achieve minimum required TOA interval (τ_p):

$$t^+_{m2} - t^+_{m1} \leq \tau_{m21}$$

$$t^+_{m3} - t^+_{m2} \leq \tau_{m32}$$

$$t^+_{mn} - t^+_{m(n-1)} \leq \tau_{m(n-1)n}$$

2. Maintain the global time performance at each active junction:

$$t^+_{m1} + t^+_{m2} + \dots + t^+_{mn} = n \cdot t_{m0}$$

3. Maintain the total flight time for each aircraft:

$$t^+_{ki} = t^-_{ki}$$

4. Limit the maximum allowable speed change below a given threshold:

$$\delta V_{im}^{m+1} \leq 0.0X \cdot V_{im}^{m+1}$$

The above cost function with its associated constraints provides an optimised set of speed changes, required to achieve the TOA changes that removes all the conflicts at any probability of aircraft simultaneous arrival at junction required to reduce ATC SM tactical interventions. This is achieved while maintaining all aircraft TTAs, overall time performance at all active junctions to keep the entropy of traffic flow network and minimising the disruption of the ATCOs' situation awareness.

6 DISCUSSION OF PRELIMINARY TEST SCENARIOS AND RESULTS

6.1 Preliminary Verification for Conflict Removal by Pre-flight TOA Changes at Junction

This section discusses two scenarios that are simulated for preliminary analysis on the possibility of conflict removal by applying optimal speed/TOA changes at pre-flight phase. For the first scenario (See Section 6.1.1), optimal speed/TOA changes are computed using the preliminary LP optimisation model described in Section 5.2. For the second scenario (See Section 6.1.2), the speed/ TOA changes are computed using the Linear Programming (LP) optimisation model discussed in Section 5.6. For both scenarios, the verification simulations are performed using the ATC2K simulator.

6.1.1 Conflict Removal by TOA Changes at a Single Crossing Active Junction

This basic scenario simulates a single pairwise conflict problem where 2 aircraft cross an active junction ($n = 2, m = 2$). The conflict is removed by applying a preliminary LP optimisation model developed in Section 5.2, to compute optimised speed changes required for both aircraft before and after the active junction that removes the conflict and maintains aircraft's Targeted Times of Arrival (TTAs). An ideal condition without uncertainties in aircraft TOAs at junction is assumed. Two flights: Flight BA560 from Oslo (ENGM) to Lisbon Humberto Delgado (LPPT) and TAP761 from Rome Ciampino (LIRA) to London Heathrow (EGLL) are simulated assuming they are flying following the great circle distance. The main characteristics of their initial Flight Plans (FPLs) are summarized in **Table 5**.

Origin-Destination/ (Flight Number)	Aircraft Type	Flight Distance (NM)	Cruise Speed (Kts)	Flight Time (Hours)
ENGM-LPPT (BA560)	A320	1537	453	3.4
LIRA-EGLL (TAP761)	A320	820	440	1.86

Table 5: Main flight information for BA560 and TAP 761 flights

The simulation is performed using ATC2K simulator. As discussed in Section 3.6, the ATC2K simulator uses a Control Working Position (CWP) as the Human Machine Interface (HMI) for controlling the air traffic. It also contains the Conflict and Risk Display (CARD) feature that displays a table containing all conflicts between aircraft pairs. It includes the predicted conflict time, the identity of the involved aircraft and other highlights [136]. **Figure 49** shows the simulated flight trajectories of the above two flights in ATC2K before the speed changes are implemented.

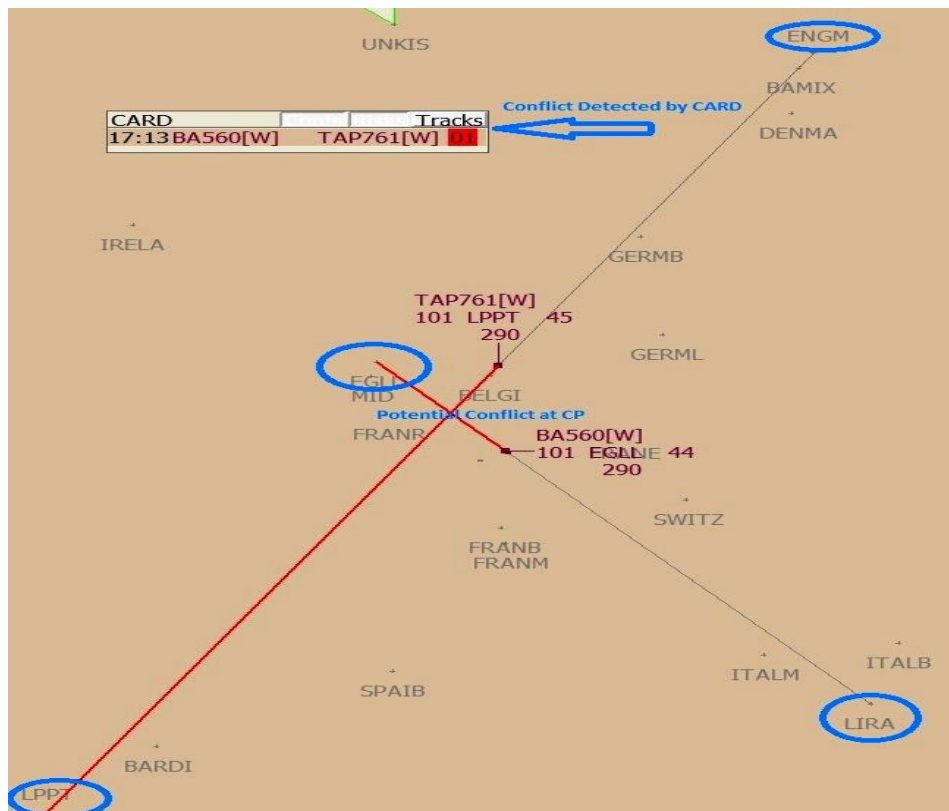


Figure 49: Detected conflict between flights BA560 and TAP761

As shown in **Figure 49**, the two trajectories share a junction at which they are detected to be in a conflict. Based on the location of the above conflicted/active crossing junction along the aircraft trajectories, the aircraft flight distance before and after the active junction are measured in ATC2K and the planned aircraft speed is obtained from their FPLs. Based on this information, the following flight parameters (before and after the active junction) required as inputs for the linear optimisation model are obtained (See Section 5.2):

Flight BA560:

$$\begin{aligned}d_{11} &= 720 \text{ NM}, d_{21} = 817 \text{ NM} \\v_{11} &= 453 \text{ kts}, v_{21} = 453 \text{ kts} \\t_{11} &= 1.589 \text{ hrs}, t_{21} = 1.804 \text{ hrs}\end{aligned}$$

Flight TAP761:

$$\begin{aligned}d_{12} &= 665 \text{ NM}, d_{22} = 155 \text{ NM} \\v_{12} &= 440 \text{ kts}, v_{22} = 440 \text{ kts} \\t_{12} &= 1.5111 \text{ hrs}, t_{22} = 0.35227 \text{ hrs}\end{aligned}$$

The minimum required safe time separation (τ) between the two flights at the junction is derived applying the conventional en-route 5 NM horizontal separation minimum.

Figure 50 shows the geometry of an active junction used to formulate τ .

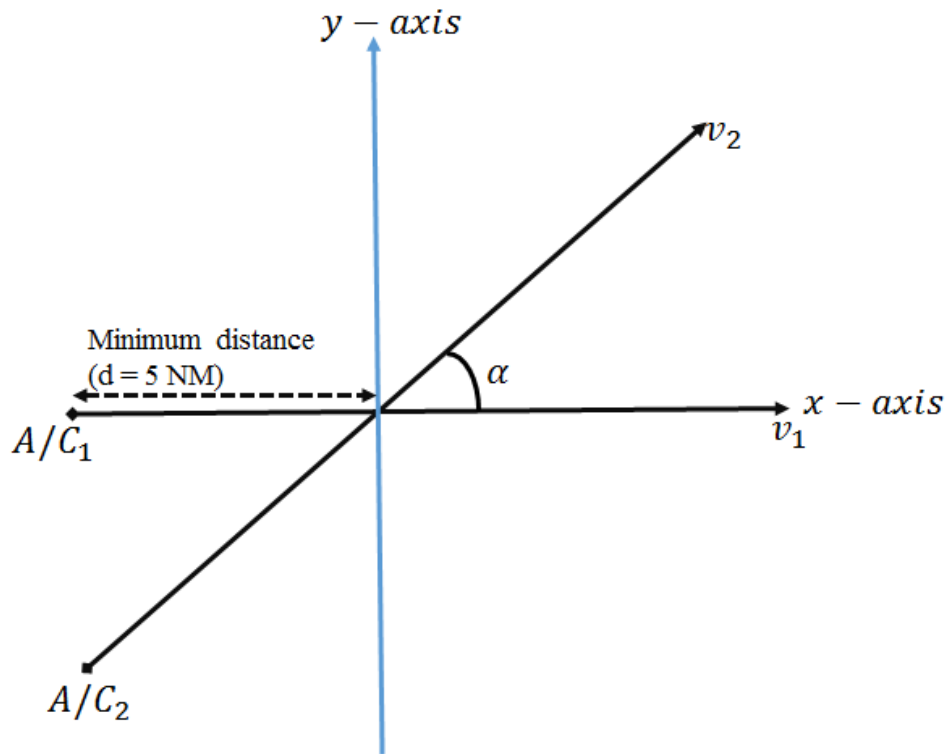


Figure 50: Geometry of conflict for deriving τ from the conventional en-route 5 NM horizontal separation minimum

From **Figure 50**, let v_1 and v_2 be the flight speed (assumed constant) for A/C_1 and A/C_2 respectively. A/C_1 is assumed the first to arrive at junction at time t and its trajectory is considered as coincident with the x-axis. A/C_2 must then arrive at junction at time $(t - \tau)$

for the conflict to be resolved. The angle α is the crossing angle between the aircraft trajectories and for flight BA560 and TAP761, $\alpha = 75^\circ$ as measured in ATC2K. To translate the conventional minimum safe separation distance ($d = 5 \text{ NM}$) into the minimum safe time separation τ at junction, the following formulation is used (See Appendix A for detailed mathematical derivation):

From **Figure 50**:

$$v_{2x} = v_2 \cos \alpha$$

$$v_{2y} = v_2 \sin \alpha$$

Let:

$$r_x = \frac{v_{2x}}{v_1}$$

$$r_y = \frac{v_{2y}}{v_1}$$

The kinematics of A/C_1 and A/C_2 are given by:

$$\begin{aligned} x_1 &= v_1 t, y_1 = 0 \\ x_2 &= v_{2x}(t - \tau), y_2 = v_{2y}(t - \tau) \end{aligned} \tag{6-1}$$

Equation (6-2) can be written from Equation (6-1):

$$\begin{aligned} (x_2 - x_1) &= v_{2x}(t - \tau) - v_1 t \\ (y_2 - y_1) &= v_{2y}(t - \tau) \end{aligned} \tag{6-2}$$

From Equation (6-2), the separation distance interval between the aircraft at junction can be given by:

$$d^2 = (v_{2x}(t - \tau) - v_1 t)^2 + v_{2y}^2(t - \tau)^2 \tag{6-3}$$

Substituting for r_x and r_y in Equation (6-2), we get:

$$\frac{d^2}{v_1^2} = (r_x(t - \tau) - t)^2 + r_y^2(t - \tau)^2 \tag{6-4}$$

The time separation τ at junction will be minimal when the derivative of Equation (6-4) is equal to zero:

$$\begin{aligned}\frac{\partial}{\partial t} \left(\frac{d^2}{v_1^2} \right) &= 2(r_x(t - \tau) - t)(r_x - 1) + 2r_y^2(t - \tau)^2 \\ &= t[r_x(r_x - 1) - (r_x - 1) + r_y^2] - \tau[r_x(r_x - 1) - r_y^2] = 0\end{aligned}\quad (6-5)$$

Solving for t in Equation (6-5):

$$t = \frac{r_x(r_x - 1) - r_y^2}{(r_x - 1)^2 + r_y^2} \tau \quad (6-6)$$

Substituting Equation (6-6) into Equation (6-4) we get:

$$\frac{d^2}{\tau^2 v_1^2} = r_x^2 + r_y^2 \frac{(r_x^2 + 2r_x + 1)}{(r_x - 1) + r_y^2} \quad (6-7)$$

Solving for τ in Equation (6-7) results:

$$\tau = \sqrt{\frac{d^2}{v_1^2(r_x^2 + r_y^2 \left(\frac{r_x^2 + 2r_x + 1}{(r_x - 1) + r_y^2} \right))}} \quad (6-8)$$

Using Equation (6-8) the required minimum safe time separation τ between aircraft at junction is computed as a function of the conventional minimum safe separation distance ($d = 5 \text{ NM}$), aircraft speed (constant and known) and the crossing angle (α) between aircraft trajectories at junction. For flight BA560 and TAP761 parameters, the value of τ is 0.3221 minutes (19.3243 seconds).

To obtain the TOA changes that are sufficient to resolve the conflict in this scenario, the preliminary LP optimisation model is run in MATLAB to compute the optimal speed changes required to ensure that the TOA minimum interval between the above aircraft

at the active junction is at least 19.3243 seconds. The outcomes of the linear optimisation are summarised in **Table 6**.

Flight	Speed change before junction	Speed change after junction
ENGM-LPPT (BA560)	+0.83020 Kts (0.183%)	−0.73125 <i>kts</i> (0.161%)
LIRA-EGLL (TAP761)	−0.71660 <i>kts</i> (0.163%)	+3.07401 <i>kts</i> (0.699%)

Table 6 : Required optimal speed changes for BA560 and TAP761 flights to remove conflict

Applying the above speed changes to the speed profile in the initial FPLs of BA560 and TAP761, results in TOA changes for both aircraft that sufficiently resolves the detected conflict. **Figure 51** shows the situation without applying speed changes (left picture) where the identified conflict (depicted in **Figure 49**) would eventually end up in a collision at the active junction. The right picture on the other hand, shows the resolved situation where the conflict has been removed after TOAs for both aircraft at the junction are timely separated by applying speed changes on both aircraft.

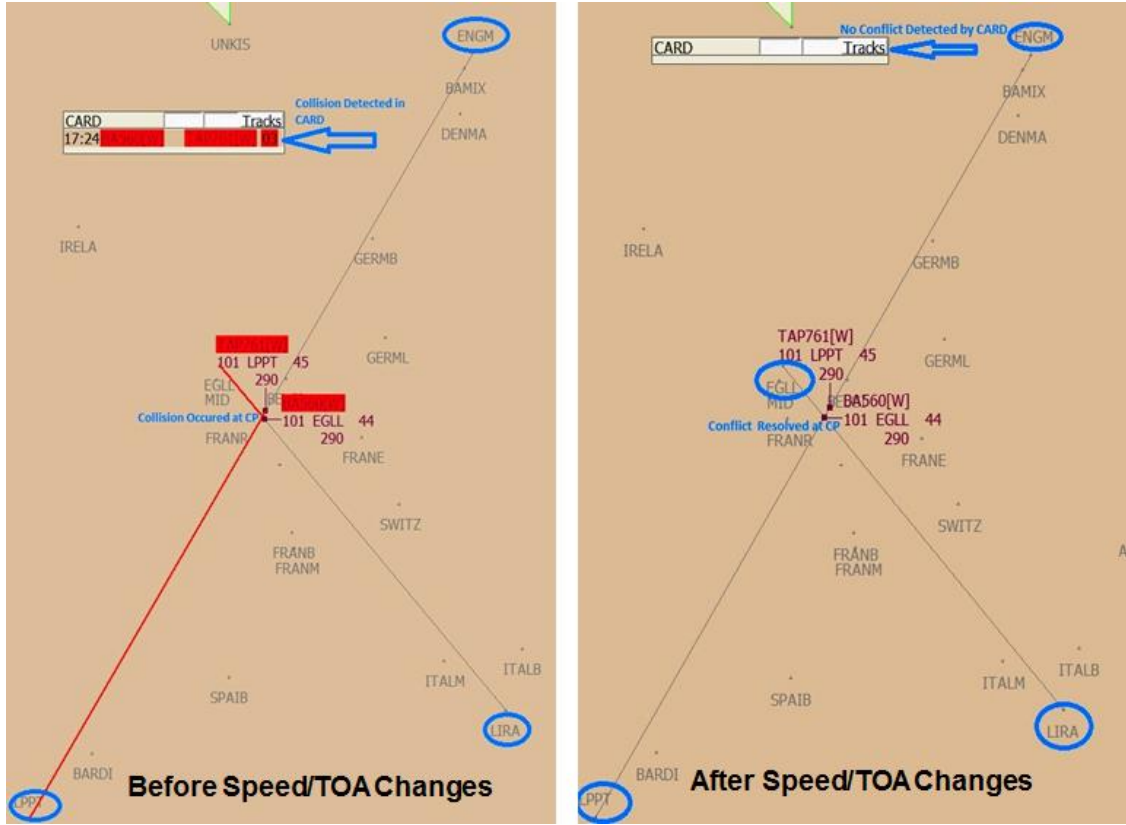


Figure 51: Situation with and without speed/TOA changes at the crossing junction of flights BA560 and TAP761

The results from this simple ($m = 2, n = 2$) junction scenario have shown that very low speed changes can sufficiently remove a conflict. However, a deterministic environment has been assumed in this scenario. Therefore, conflict-free trajectories in an environment with non-deterministic factors involved cannot be ensured. This is because this scenario has omitted the characteristics of TOA uncertainties at junction and may have generated unrealistic solutions. For this reason, the subsequent sections discuss scenarios where the optimal speed changes are computed considering aircraft TOA at junction uncertainties.

6.1.2 Conflict Removal at Single and Multiple Crossing and Merging Junctions

Different scenarios of aircraft involved in conflicts at junctions, with different initial time separation interval between any two consecutive aircraft at junctions (τ_0) and the number of junctions (single junction or multiple junctions) along aircraft trajectories are

discussed in this section. The required speed changes to resolve the conflicts are computed using the LP optimisation model developed in Section 5.6 which accounts for the TOA uncertainties through its minimum required TOA interval (τ_p) constraint.

It is necessary to recall from Equation (5-38), that τ_0 is defined as the nominal time separation interval between any two consecutive aircraft at junction before speed changes are applied. This variable represents the interdependency of time stamps on aircraft trajectories at junctions. In other words, it represents the closeness of any two consecutive aircraft at junction that is inherent in aircraft's initial FPLs.

For each scenario in this section, the expected probability of aircraft simultaneous arrival at junction is set to 10^{-5} . Such a low probability as discussed in Section 5.5 should results in a low conflict risk among any en-route air traffic scenario and should then significantly reduce the current ATC SM tactical interventions. To achieve the P_C value of 10^{-5} requires a minimum TOA interval (τ_p) at junction between any two consecutive aircraft of approximately 9.4 minutes (see **Figure 46**). In order to obtain the required TOA changes for each aircraft that achieves the above probability, the optimisation model is applied for each considered scenario in this section. The results are then simulated in the ATC2K simulator software to verify the successful conflict removal.

The Single Merging Junction Scenario: In this example of a merging conflict scenario, six aircraft merging at a single junction are considered. It is necessary to note, that six aircraft per hour have been previously determined in Section 5.5 as the allowed approximate maximum inbound traffic flow rate at junction that achieves a probability of aircraft simultaneous arrival of 10^{-5} . In other words, six aircraft per hour is the approximate maximum inbound traffic flow rate required to respect the minimum time interval (τ_p) of 9.4 minutes between any two consecutive aircraft at junction.

To remove the conflicts, the optimal speed changes are computed for each aircraft before and after the junction in order to achieve the above-required TOA interval, whilst maintaining the TTA at the final destination waypoint of each aircraft.

All aircraft in this scenario are assumed to fly at the same speed of 450 Kts with a flight distance of 900 NM to the junction. The value of the initial/nominal time separation interval (τ_0) between any two consecutive aircraft at junction is randomly generated within different TOA separation interval ranges of [0, 9], [0, 8], [0, 7], [0, 6], [0, 5], [0, 4] minutes. Each of the above TOA separation interval range represents a different initial time stamp interdependency of aircraft trajectories at the junction before TOA changes are applied. For example, when τ_0 values are generated from the interval [0, 7], the generated initial/nominal time separation interval between: A/C1 and A/C2, A/C2 and A/C3, A/C3 and A/C4, A/C4 and A/C5, A/C5 and A/C6 at junction could be 2, 5, 6, 4, 0, 7 minutes respectively or any other sequence with random integers that are ≥ 0 and ≤ 7 . For each initial/nominal TOA separation interval range, a different conflict situation is generated. Since any random τ_0 value that can be generated from the above interval ranges is below 9.4 minutes, all the above TOA separation interval ranges represent traffic inbound flow rates that are above the throughput of the junction.

Figure 52 shows box and whisker plots of the aircraft speed changes (in percentage of aircraft nominal speed), computed by the LP optimisation model to remove the conflict situations for each of the above TOA separation interval ranges. As shown in **Figure 52**, for random τ_0 values generated within TOA separation interval ranges of [0, 9] minutes and [0, 8] minutes, the obtained speed changes are all below 6%. For the TOA separation interval range of [0, 7] minutes, more than the 50th percentile is below 6%, whereas for [0, 6], [0, 5] and [0, 4] TOA separation interval ranges, more than the 50th percentile is above 6% speed change. For all these situations, the speed changes required of any of the involved aircraft to resolve the conflict are below 12% speed change. These merging conflict scenarios are verified through a series of simulations using ATC2K simulator and the conflicts are successfully removed.

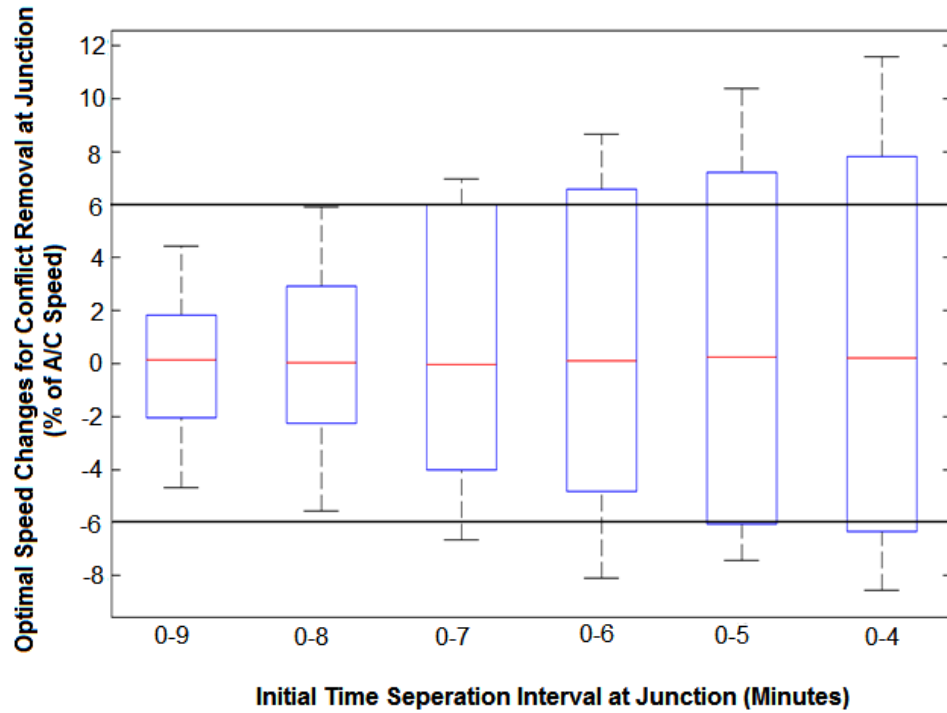


Figure 52: Statistics of required speed changes for a scenario of six aircraft merging to a junction for different randomized initial TOA separation interval ranges at junction.

The Scenario for Multiple Active Junctions along Trajectories: As discussed in Section 5.6, an aircraft may be in conflict at multiple junctions along its trajectory. **Figure 53** illustrates a two-active-junction scenario involving 8 aircraft where the aircraft denoted as A/C4 is in a conflict with other five aircraft at junction *m* and also in a conflict with other two aircraft at junction *n*.

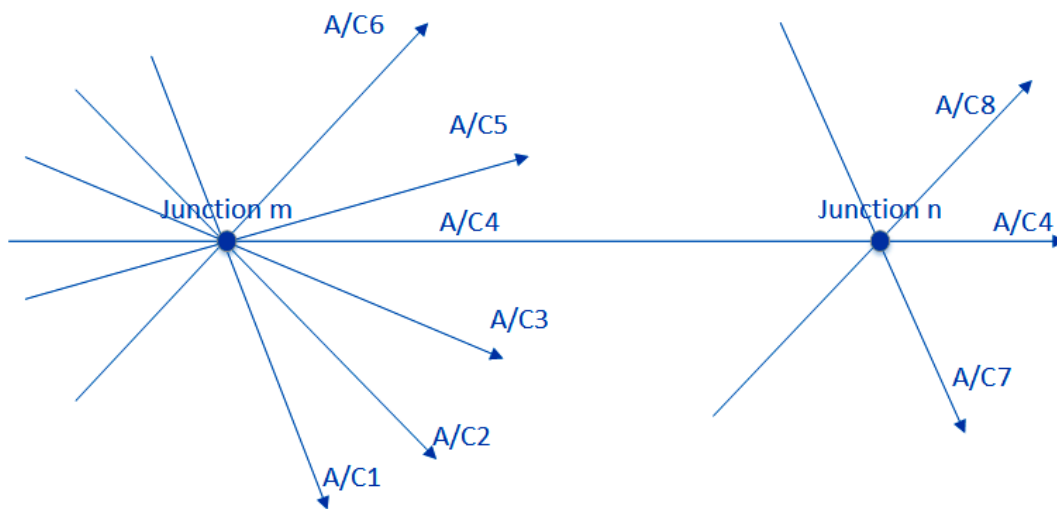


Figure 53: Illustration of multiple active junctions along trajectory

The scenario depicted in **Figure 53** is developed using the same six aircraft used in the previous single merging junction scenario for the first junction m , and extra two aircraft at the second junction n that are in a conflict with $A/C4$ along its trajectory. The optimisation model is applied to provide the required speed changes that remove all the conflicts at both junctions, considering the aforementioned different TOA separation interval ranges at the junction. The results are summarised in **Table 7**.

τ_0 variation interval Ranges (Minutes)		0-9	0-8	0-7	0-6	0-5	0-4
Optimal Speed Changes (% of A/C's Speed)	A/C	First Active Junction					
	A/C1	3.2731 -2.5738	4.5429 -3.5542	5.1760 -5.4552	8.9412 -8.2804	10.8340 -10.8359	13.1296 -13.3052
	A/C2	2.7878 -2.8995	5.3553 -5.4498	5.9990 -5.9438	7.6717 -7.1567	7.6493 -7.0368	9.6664 -8.3386
	A/C3	0.0574 -0.0694	2.3431 -2.7684	3.5855 -4.0640	2.3202 -2.4374	4.4268 -3.6789	1.9553 -2.9741
	A/C4	-1.4753 2.0553	-2.2932 3.7668	-3.2656 4.3484	-4.5493 5.2258	-5.9951 6.4911	-6.9895 7.5226
	A/C5	-2.1186 3.3740	-1.9689 3.0780	-4.9123 4.0083	-4.4023 7.4302	-5.2166 7.5429	-7.0531 9.6725
	A/C6	-2.1179 3.8212	-4.7596 5.2369	-6.1979 5.5880	-7.6655 8.9412	-9.7612 10.4107	-10.4172 13.5992
		Second Active Junction					
	A/C7	0.2088 -0.4149	1.6289 -2.2346	2.2211 -3.2773	3.6421 -4.2900	4.3454 -5.3825	6.2088 -6.4149
	A/C8	-0.5419 1.2658	-2.9138 2.1010	-3.6578 3.0961	-4.9138 4.1277	-0.5110 5.1211	-6.7413 5.7658
	A/C4	-4.8405	-6.4374	-6.2267	-7.7065	-11.7581	-13.5360

Table 7: Required optimal speed changes for multiple active junctions

Figure 54 shows the statistics for the optimal speed changes required to resolve the conflicts in this scenario. It can be observed that the optimal speed changes obtained in this scenario are still below 6% for randomised τ_0 values generated within initial TOA separation interval ranges of [0, 9] minutes and [0, 8] minutes. For the [0, 7] minutes initial TOA separation interval range, speed changes within 6% are still more than the 50th percentile where the speed changes for interval ranges [0, 6] minutes and [0, 5] minutes remain within 12%. For the interval range [0, 4] minutes, the 100th percentile slightly increases above 12% speed change.

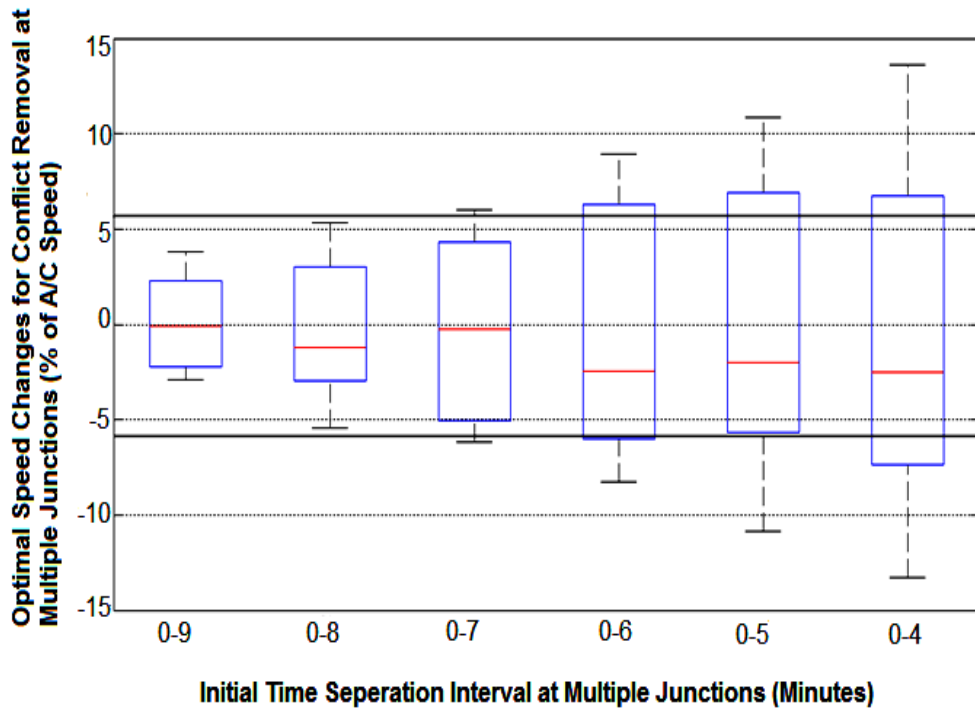


Figure 54: Statistics of the required speed changes for a scenario of multiple converging active junctions involving six aircraft at the first junction and three aircraft at the second junction.

In conclusion, the results above shows that conflicts can be effectively removed through aircraft TOA adjustments at junction, achieved by optimal speed changes applied to aircraft FPLs' speed profiles. In addition, since the linear programming is used, the common scalability problem in ATFCM optimisation should be minimal when the proposed method is applied to real high traffic density scenarios. These scenarios are discussed in Chapter 7.

6.2 Preliminary Testing and Analysis of TOA Adjustments for Feasibility Application to ATFCM DCB

This section discusses three sets of scenarios; the first set of scenarios is simulated to verify the LP model characteristics at different traffic densities (See Section 6.2.1). The second set of scenarios is simulated to analyse the behaviour of LP model in situations where the arriving traffic demand exceeds the junctions inbound flow capacity (See Sections 6.2.2, 6.2.3 and 6.2.4). The last set of scenarios is used for basic analysis of the

effect of the proposed ATFCM DCB method on the flight operating costs (See Section 6.2.5).

6.2.1 Realistic Number of Inbound Aircraft in a Set for De-confliction

In Chapter 2, it was acknowledged from the literature that the reactive nature of current ATM system favours tactical de-conflicting techniques such as heading and flight level changes over speed control technique. It was also identified that this is mainly due to the significant anticipation time required by speed control and the limited feasible speed changes that can be tactically applied in compatibility with the aircraft performance. It was also understood that those measures are preferred especially because conflicts are currently detected tactically and locally, leading to use of heading and flight level changes (reactive techniques) to resolve them.

If hotspots can be identified long time in advance at pre-flight phase, it can allow the ATFCM to use aircraft speeds as control variables to mitigate them at pre-flight phase. However, this can only be realistically achieved when the optimal speed changes that are applied to aircraft produce minor changes on the aircraft TOAs at junctions. The solution is also feasible only when these TOA changes demand very small speed changes from the involved aircraft.

By imposing realistic maximum speed change thresholds (see Equation (5-44)) that are compatible with aircraft performance (e.g., 6% or 10%) as a constraint in the LP model, a number of aircraft in a set inbound an active junction that can be successfully de-conflicted without exceeding the above speed change thresholds can be determined. This is particularly important in determining the performance of the proposed ATFCM DCB method when the traffic density at the junctions is high such as on busy Air Traffic Service (ATS) route network junctions.

In this discussion, a set of aircraft in-bound a junction is understood as a sequence of two or more aircraft planning to arrive at junction within a given period of time, representing the air traffic demand of junction for that period of time. A time length of one hour is used as the period in the scenario discussed in this section. Therefore, if a set of six aircraft inbound a junction has exactly the established minimum TOA

separation of 9.4 minutes between any two consecutive aircraft, the junction would be then operating on approximately its full nominal throughput.

Figure 55 shows box and whisker plots for the speed changes (in percentage of nominal aircraft speed) required to remove conflicts at a junction, for different numbers of aircraft in a set inbound a junction in a period of one hour. The earlier defined initial time separation interval (τ_0) between any two consecutive aircraft at the junction before applying speed changes is randomly generated within the range of [0, 9] minutes, following a uniform distribution. Generating τ_0 values from a range of [0, 9] minutes implies that each aircraft involved in the scenario is initially in a conflict at junction, considering that a minimum TOA separation interval at junction of $\tau_p = 9.4$ minutes used in the previous section is maintained.

To compute the required optimal speed changes presented in **Figure 55**, the linear optimisation model is applied to achieve the above minimum TOA separation interval (i.e. $\tau_p = 9.4$ minutes) between any two consecutive aircraft at junction, resulting into a probability of aircraft simultaneous arrival at junction (P_c) of 10^{-5} as previously established.

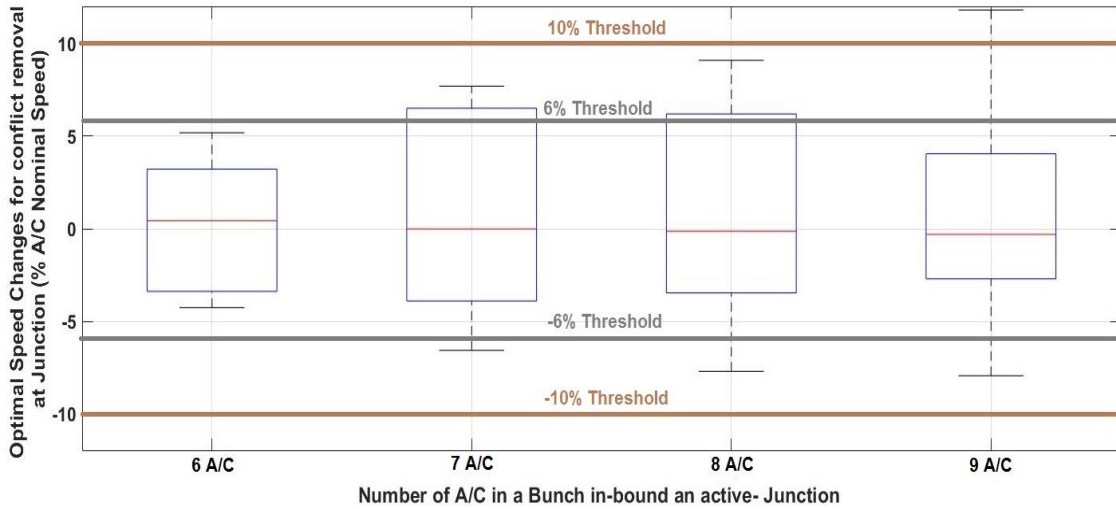


Figure 55: Optimal speed changes for different numbers of aircraft in a set inbound a junction

As shown in **Figure 55**, for a set of six aircraft inbound a junction, the obtained speed changes are all below the 6% threshold. As the number of inbound aircraft in a set increases, the required optimal speed changes to remove the conflicts also increases. When the number of inbound aircraft increases from six aircraft to seven aircraft and subsequently to eight aircraft, approximately 50th percentile of speed changes are exceeding the 6% threshold, despite all aircraft are within the 10% threshold.

Figure 55 also shows that when the number of inbound aircraft increases to nine aircraft, the 10% threshold is exceeded. This implies that if a maximum speed change of 6% and 10% is required for $\tau_0 \in [0, 9]$, the number of aircraft in a set inbound a junction in one hour must not exceed six and eight, respectively. This exercise can be performed for any τ_0 interval and for any speed change threshold, reflecting a particular traffic situation at junction that can be realistically de-conflicted with respect to aircraft performance constraints.

Figure 56 and **Figure 57** show the computed optimal speed changes (in percentage of nominal aircraft speed) before and after the junction for each aircraft when $\tau_0 \in [0, 9]$. The number of inbound aircraft to the junction in an hour is set to 12 (**Figure 56**) and is then increased to 15 (**Figure 57**). It can be seen from **Figure 56** that the middle six aircraft (*A/C4*, *A/C5*...*A/C8* and *A/C9*) and the middle eight aircraft (*A/C3*, *A/C5*...*A/C9* and *A/C10*) are within 6% and 10% speed change threshold, respectively. Similarly, from **Figure 57** the middle six aircraft (*A/C6*, *A/C7*...*A/C10* and *A/C11*) and the middle eight aircraft (*A/C4*, *A/C5*...*A/C10* and *A/C11*) are within 6% and 10% speed change threshold, respectively. The results in both **Figure 56** and **Figure 57** substantiates the results portrayed in **Figure 55** that if a maximum speed change of 6% and 10% is required for $\tau_0 \in [0, 9]$, the number of aircraft in a set inbound a junction in one hour must not exceed six and eight, respectively. These results also indicate that for any number of aircraft inbound a junction in a set, the middle aircraft in the arrival sequence require smaller speed changes to remove the conflict relative to the first few and last few aircraft in the arrival sequence. This is due to monotonic increase of speed/TOA changes required for the first few and last few aircraft in the arrival sequence to remove the

conflict when the arriving traffic demand exceeds the junctions inbound flow capacity, as further discussed in Section 6.2.2.

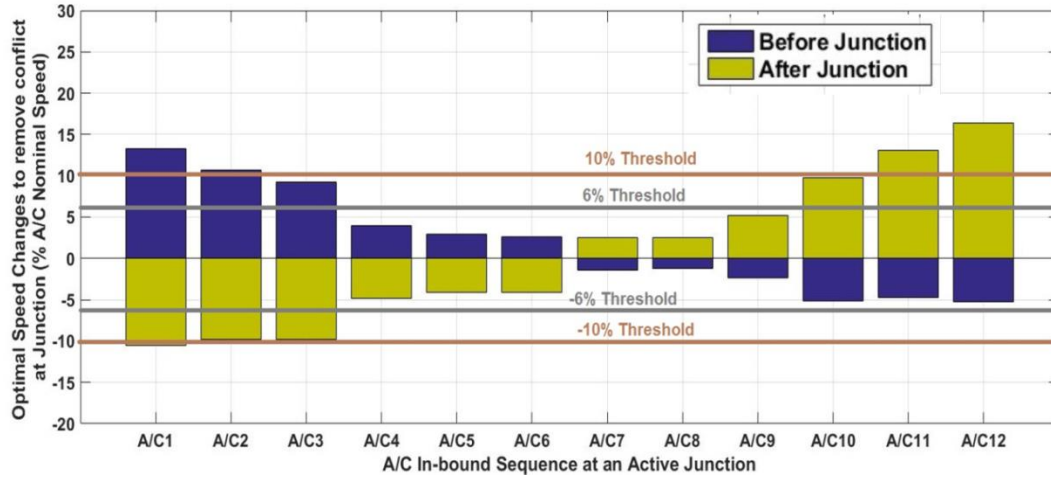


Figure 56: Optimal Speed changes per aircraft for 12 aircraft in a set inbound a junction

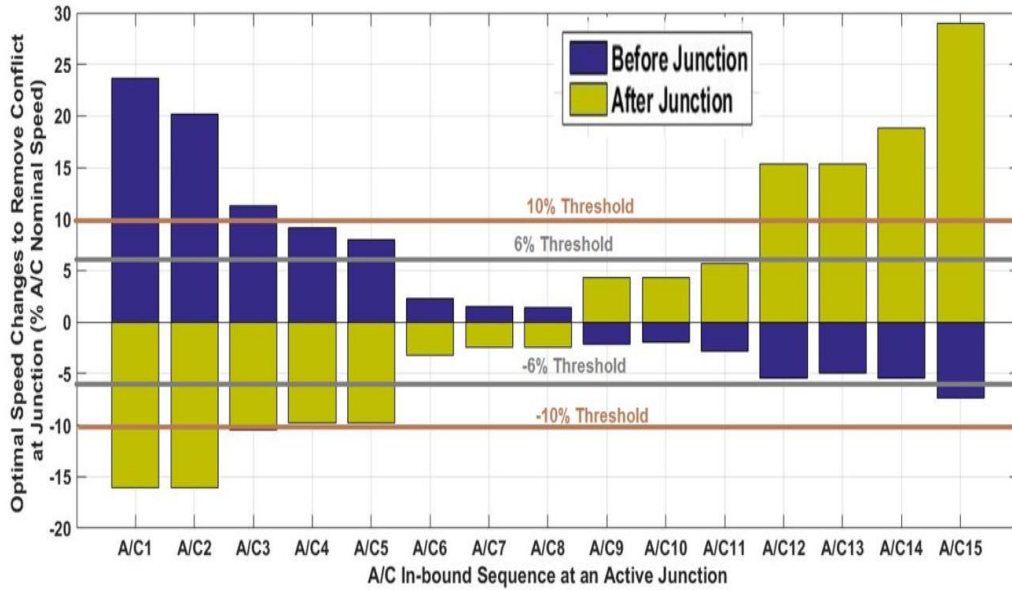


Figure 57: Optimal Speed changes per aircraft for 15 aircraft in a set inbound a junction

6.2.2 The Monotonic Increase of Speed /TOA Changes when Demand is Above Junction's Inbound Flow Capacity

As previously stated, when $\tau_0 \in [0, 9]$ minutes, for any number of aircraft in a set inbound a junction, all of these aircraft are initially in conflict at that junction. This

implies that TOA changes are required for each aircraft in order to achieve the required TOA minimum separation ($\tau_p = 9.4$ minutes) and remove all conflicts at that junction with a $P_c = 10^{-5}$.

For example, for eight aircraft in a set inbound a junction as shown in **Figure 58**, seven minimum TOA separation intervals are required with 9.4 minutes (approximated to 9 minutes) each between any pair of consecutive aircraft to remove successfully all conflicts with a $P_c = 10^{-5}$. To achieve this, it then follows that an interval of at least $7 \times 9 = 63$ minutes at a junction is required between the first aircraft to arrive at junction (A/C1) and the last aircraft in the set to arrive at junction (A/C8).

In **Figure 58**, two situations of initial TOA separations at junction are simulated. In the first situation (the top horizontal line), τ_0 is randomly generated within a TOA separation interval range of $[0, 7]$ minutes ($\tau_0 \in [0, 7]$) providing specific random initial TOA separations at junction of 2, 5, 6, 4, 0, 5 and 2 minutes between AC1&AC2...AC7&AC8 respectively (See **Table 8**). By adding these specific random initial TOA separations, the situation then results in an initial separation interval between the first and last aircraft of 24 minutes (shown by the top line interval) in **Figure 58**. In the second situation where $\tau_0 \in [0, 3]$ minutes, the result provides specific random initial TOA separations at junction of 1, 2, 3, 2, 0, 2 and 1 minutes (See **Table 8**). These separations result in an 11 minute initial separation interval between the first and last aircraft for the same set of aircraft (shown by the bottom line interval) in **Figure 58**.

Aircraft pair	AC1& AC2	AC2& AC3	AC3& AC4	AC4& AC5	AC5& AC6	AC6& AC7	AC7& AC8	AC1& AC8
τ_0 interval (minutes) for situation with $\tau_0 \in [0,7]$	2	5	6	4	0	5	2	24
τ_0 interval (minutes) for situation with $\tau_0 \in [0,3]$	1	2	3	2	0	2	1	11

Table 8: Generated random initial aircraft TOA separations at junction

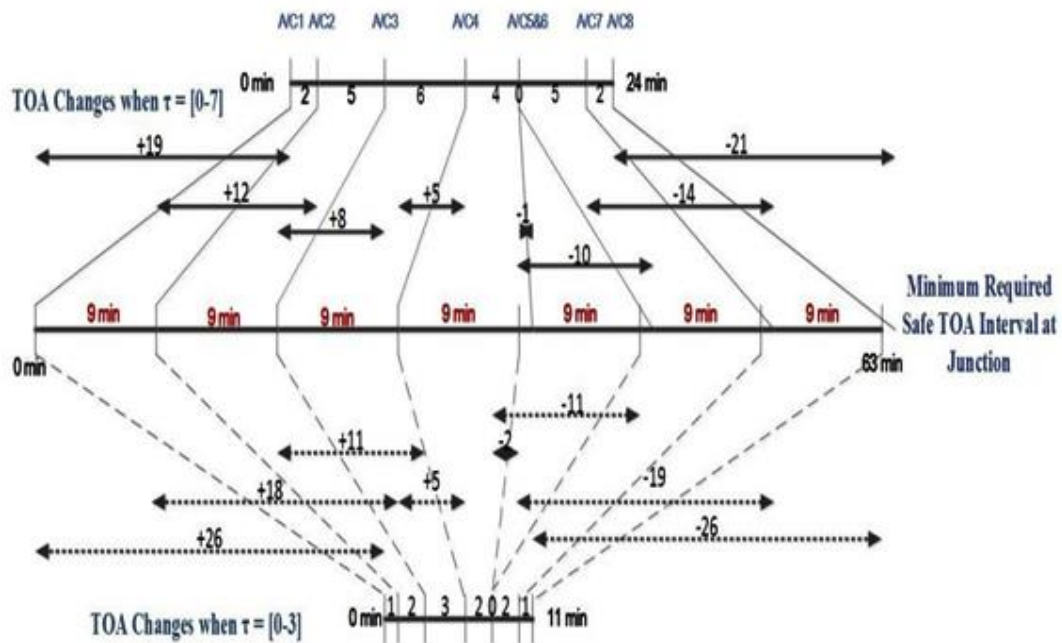


Figure 58: Examples of monotonic increase of TOA changes when $\tau_0 \in [0, 9]$

It can be seen in each of these two situations of initial TOA separations at junction, that it is necessary to change the TOAs of the first and the last aircraft long enough to obtain an interval of at least 63 minutes between them at junction (see middle line in **Figure 58**). For example, *A/C1* is required to allow an additional 19 minutes to remove conflicts when $\tau_0 \in [0, 7]$ minutes whilst it should be extended longer (26 minutes) for the case when $\tau_0 \in [0, 3]$ minutes, as illustrated in **Figure 58**". These changes should provide the required total minimum safe separation time scale (63 minutes) on which all

middle aircraft TOAs can be effectively changed to achieve the minimum 9 minutes required for safe separation at junction between each consecutive pair of aircraft in the set. As also shown in **Figure 58** for both situations, the first and the last few successive aircraft in a set usually require TOA changes longer than the required minimum separation time (i.e. 9 minutes) whilst the middle aircraft only require shorter TOA changes that are just enough to achieve the 9 minutes minimum separation at junction between them.

To compare the results of these two simulated situations in **Figure 58**, the optimal TOA changes for the case when $\tau_0 \in [0, 7]$ minutes are shown by solid lines with two arrow ends, drawn above the middle line, where the optimal TOA changes for the situation when $\tau_0 \in [0, 3]$ are shown by dashed lines with two arrow ends, drawn below the middle line. From these results, it can be easily derived that the stronger the initial time stamp interdependencies/closeness (i.e. the smaller the τ_0) of aircraft trajectories at the junction before TOA changes are applied, the much longer the TOA changes are required for the first and the last few aircraft in a set to arrive at junction. On the other hand, the TOA changes for the middle aircraft are merely affected by the initial time stamp interdependencies (τ_0 range size). Similar behaviour is also reflected in the aircraft optimal speed changes obtained for the above two situations. This phenomenon is shown in **Figure 59** for $\tau_0 \in [0, 7]$ and in **Figure 60** for $\tau_0 \in [0, 3]$. By comparing the results in these two figures, it can be observed that when τ_0 is decreased from $[0,7]$ minutes to $[0,3]$ minutes, the optimal speed changes required to remove conflicts strictly increases monotonically for the first and the last few aircraft in a set whilst it remains almost linear for the middle aircraft.

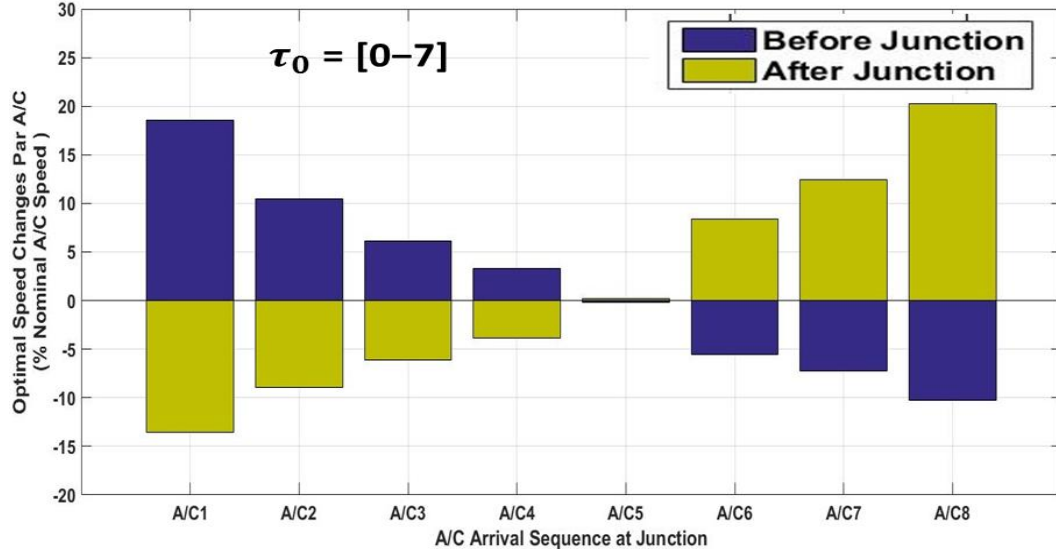


Figure 59: Optimal speed changes when $\tau_0 \in [0, 7]$

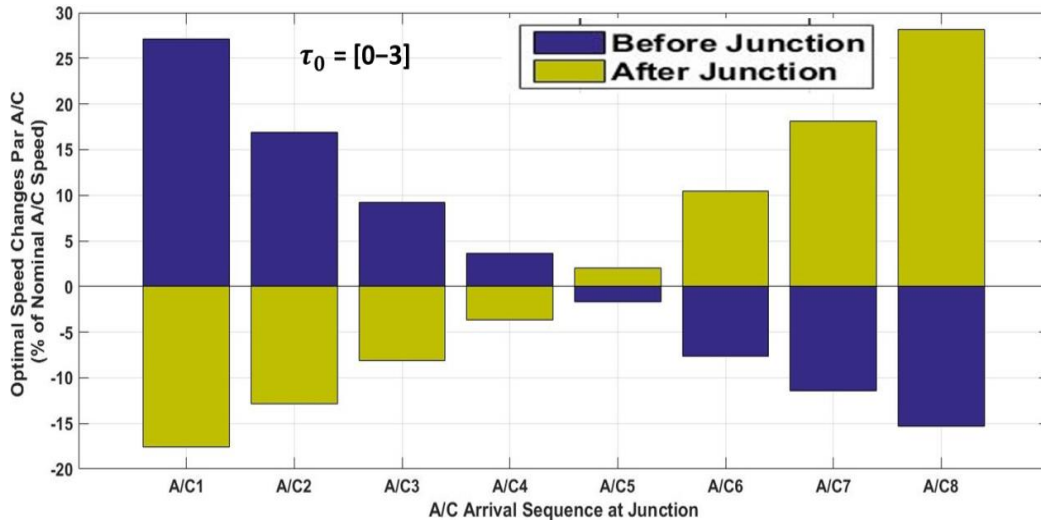


Figure 60: Optimal speed changes when $\tau_0 \in [0, 4]$

The above monotonic increase in the speed/TOA changes can be attributed to the fact that when τ_0 is below $[0, 9]$ minutes; the demand of arriving traffic is above the junction's inbound flow capacity (QI_m). This may particularly occur at merging junctions where the incoming traffic is confined into higher density outbound routes. This behaviour is usually observed in all other single server queuing systems, where the traffic delay grows without bound whenever the traffic arrival rate exceeds the servers inbound flow capacity.

6.2.3 The Modulation of Speed/TOA Changes to Remove the Monotonic Behaviour

As discussed in Section 5.5, an inbound flow capacity of a junction is sensitive to the uncertainties of aircraft's TOA at junction. This implies that when confining air traffic in a fixed conventional ATS route network and considering the aircraft TOA uncertainties modelled in Section 5.3, the proposed ATFCM DCB method could become unrealistic in very high-density situations. Therefore, this thesis postulates that in the future most aircraft will be able to fly under the procedures of Free Routing Airspace (FRA) where the number of routes intersections is fairly spread out with the traffic density at junctions low, except at the entry points of high density TMAs. For the crossing junctions and for merging junctions beyond TMAs, which are considered in the scope of this thesis (See Section 4.3), the ATS route network will usually have traffic flow below their capacity limits. Under these circumstances, the proposed ATFCM DCB method will then be dealing with a traffic de-randomisation problem (speeding up and slowing down arriving traffic) to achieve a minimum “safe” time interval among aircraft arriving from different links.

Under the above postulated circumstances, it is possible to have situations of τ_0 intervals greater than $[0, 9]$ minutes such that initial separation greater than 9 minutes between some pairs of consecutive aircraft in a set inbound a junction can be realistically assumed. This allows several aircraft to be initially sufficiently separated at junctions. For those aircraft that are initially sufficiently separated, their TOA separation at junction can be reduced to exactly the minimum required safe separation (9 minutes) in order to better accommodate speed/TOA changes among all aircraft. Hence, tackling the traffic de-randomization problem and at the same time maximising the junction's utilization/throughput by speeding up and slowing down arriving traffic to achieve exactly the required minimum “safe” time interval among all aircraft arriving to all active junctions from different links of the network. This solution removes the previously identified monotonic behaviour of speed/TOA changes in the first and last aircraft in a set, therefore, providing some degree of fairness in the allocation of speed changes among all involved aircraft in removing conflicts.

Figure 61 and **Figure 62** show the computed optimal speed changes when a set of 8 aircraft in-bound to a junction is considered when $\tau_0 \in [0, 12]$ minutes and $\tau_0 \in [0, 15]$ minutes, respectively. The results in these figures show that as τ_0 increases above $[0, 9]$ minutes, the monotonic behaviour in the required speed changes for the first and the last aircraft arriving at junction (observed in **Figure 59** and **Figure 60**) have subsequently changed into an oscillated behaviour. An oscillated behaviour of speed changes is understood as having a possibility where some aircraft in the arrival sequence at junction, could require moderately higher speed changes than the first and the last aircraft in the sequence to remove conflict.

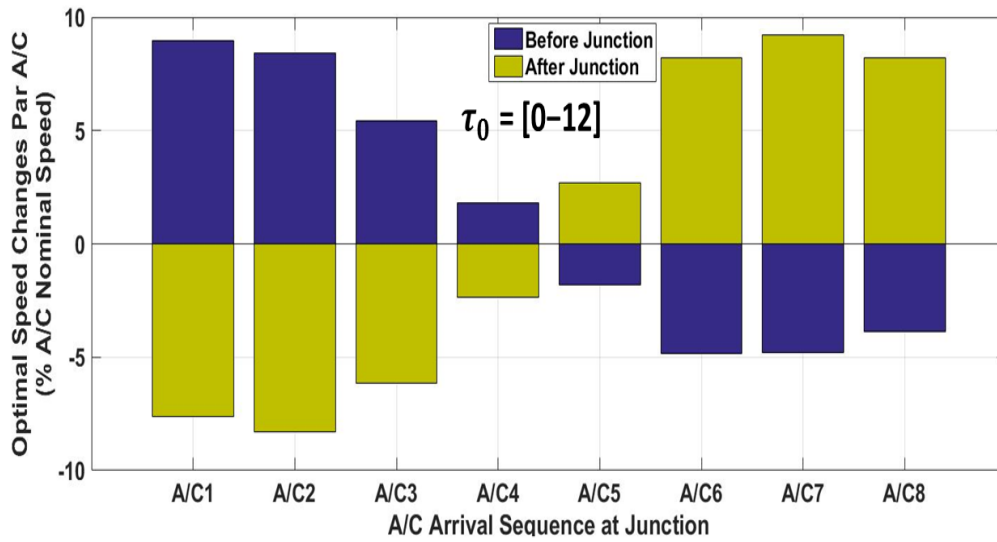


Figure 61: Oscillated behavior of speed changes when $\tau_0 \in [0, 12]$

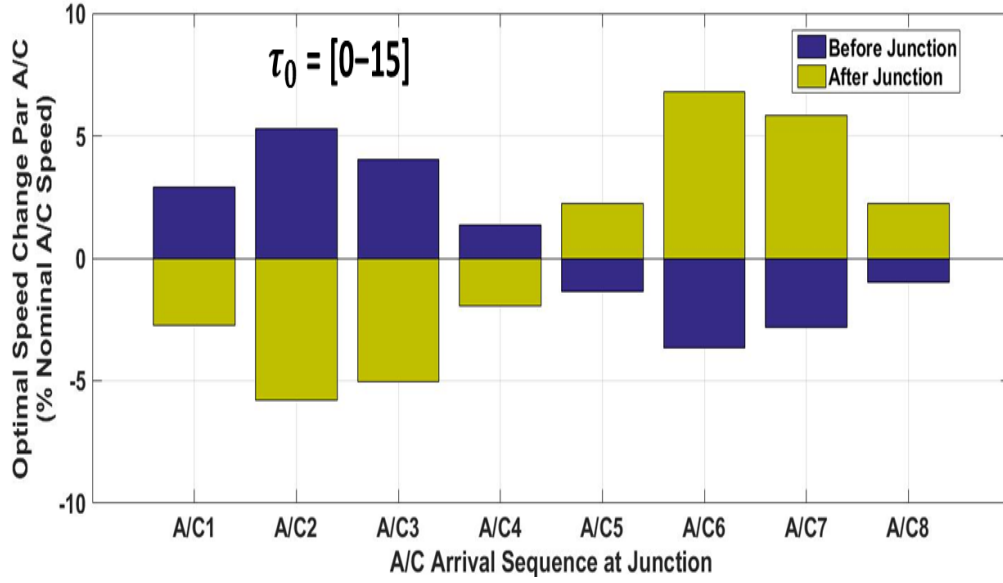


Figure 62: Oscillated behavior of speed changes when $\tau_0 \in [0, 15]$

6.2.4 The Speed/TOA Changes' Steady State Conditions

When the initial TOA separation at junction is further increased such that $\tau_0 \in [0, 18]$ minutes, the junction's inbound flow capacity (QI_m) exceeds the arriving traffic demand, and the optimal speed changes reaches the stable steady state as shown in **Figure 63** and **Figure 64** for $\tau_0 \in [0, 18]$ minutes and $\tau_0 \in [0, 20]$ minutes respectively. This stable state is attributed to the fact that, when $\tau_0 \in [0, 18]$ minutes, and the initial separation between any two consecutive aircraft at junction is randomly generated in this interval, the resulting average TOA initial separation between aircraft is close to 9 minutes which is the required minimum safe separation at the junction.

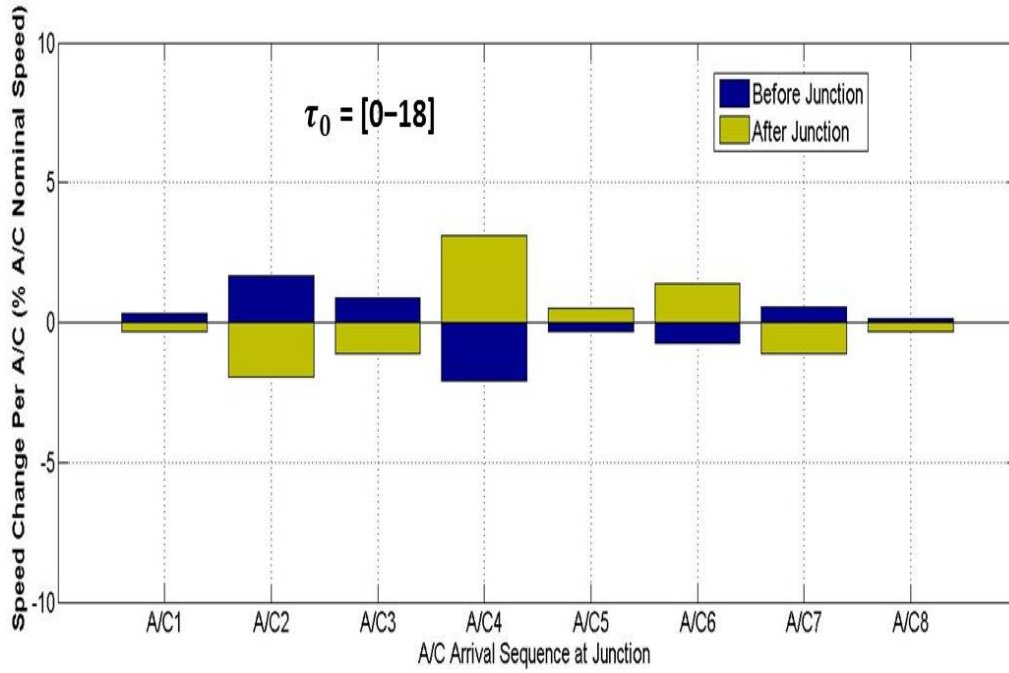


Figure 63: Stable steady state when $\tau_0 \in [0, 18]$

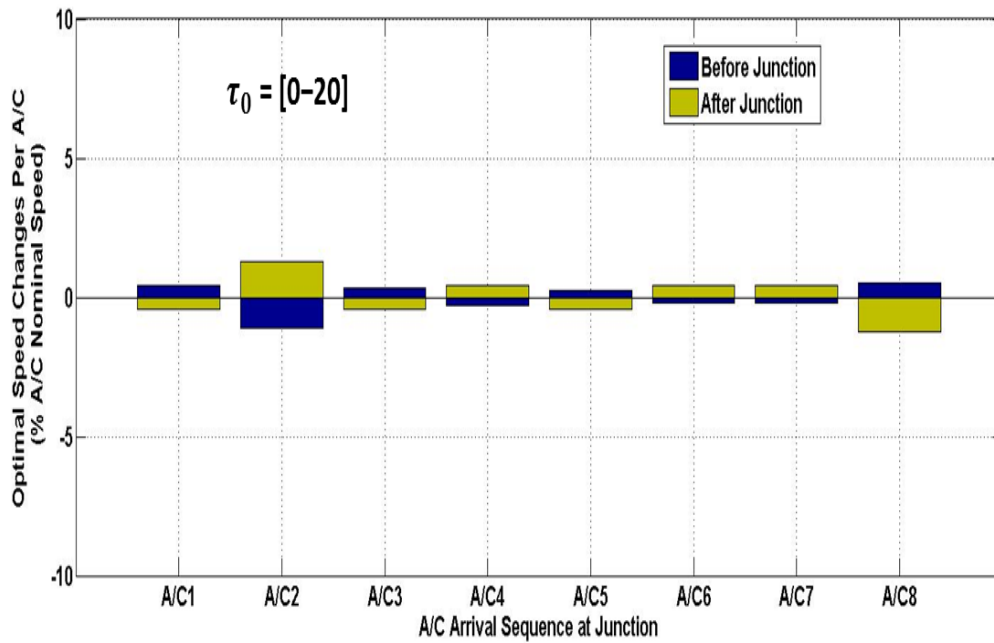


Figure 64: Stable steady state when $\tau_0 \in [0, 20]$

6.2.5 The Effect of Optimal Speed Changes on Flight Operating Costs

As discussed in Section 2.6, the flight operating costs in commercial aviation can be divided into fuel costs, flight time dependent costs and fixed costs. The fixed costs such

as crew and landing fees are independent of the flight speed, while fuel and time costs vary as a function of the flight speed. Fuel costs and flight time costs are part of aircraft Direct Operating Costs (DOC), which also includes other cost elements such as aircraft depreciation and maintenance costs [94]. For the purpose of this thesis, flight-operating costs only imply fuel costs and flight time costs. AUs have different operating objectives, and hence, the flight operating cost optimisation is proprietary and varies from one AU to another. In this context, some AUs may prefer timely flights while others are more concerned with fuel savings. To achieve this trade-off as discussed in Section 2.6, different flights use different Cost Index (CI) values through an optimisation process, which has a common global objective function given by: $\text{TotalCost} = (\text{fuelcosts}) + \text{CI} \times (\text{Timecosts})$.

Given that, CI is proprietary to the AU and is not usually shared outside an airline, it is assumed constant and same for all flights in this thesis. Moreover, one important attribute of the proposed LP optimisation model used to compute TOA/Speed changes, is that it preserves the aircraft's departure time and TTA, therefore, does not affect flights' time related costs. Hence, the optimal speed changes computed by the model only affects the amount of fuel consumed by the flight.

To enable a preliminary analysis on the effect of the computed optimal speed changes on the aircraft's fuel consumption, a scenario is developed and simulated using data from Base of Aircraft Data (BADA) model (See Section 3.6) to establish the amount of fuel consumed in this scenario when speed changes are applied to an aircraft's speed profile at pre-flight phase. To analyze this effect, the amount of fuel consumed in this scenario is compared to the aircraft's nominal fuel consumption obtained using a benchmark scenario considering different numbers of aircraft in a set inbound a junction with different τ_0 values applied. In this analysis, the aircraft nominal fuel consumption is defined as the amount of fuel that the aircraft consumes if its initial planned cruise speed is not changed; assuming that this initial planned speed is the optimal speed for fuel consumption in the AUs perspective. This definition implies that, any change on the aircraft speed (whether an increase or decrease in aircraft's speed), result into excess costs to the AUs.

The A320 is used in this analysis; this is because it is a typical mid-range aircraft commonly used in Europe, hence, it is assumed a good representative of the vast majority of European flights, either operated by low-cost or legacy carriers.

It is acknowledged that the aircraft's fuel consumption varies with the weight and flight altitude, but in order to have significant results, it is assumed that the weight of the aircraft throughout the flight is the average weight of the aircraft during cruise, and a flight level of 37000 feet is selected and unchanged during the flight. BADA aircraft performance model is used to extract the aircraft's performances used to compute the fuel consumption. **Figure 65** shows the average change in fuel consumption per aircraft for sets of 6, 9, 12, and 15 aircraft inbound a junction and τ_0 values randomly selected from $\tau_0 \in [0, 9]$, $[0, 12]$, $[0, 15]$ and $[0, 18]$, when the speed changes are applied to remove conflict at junction.

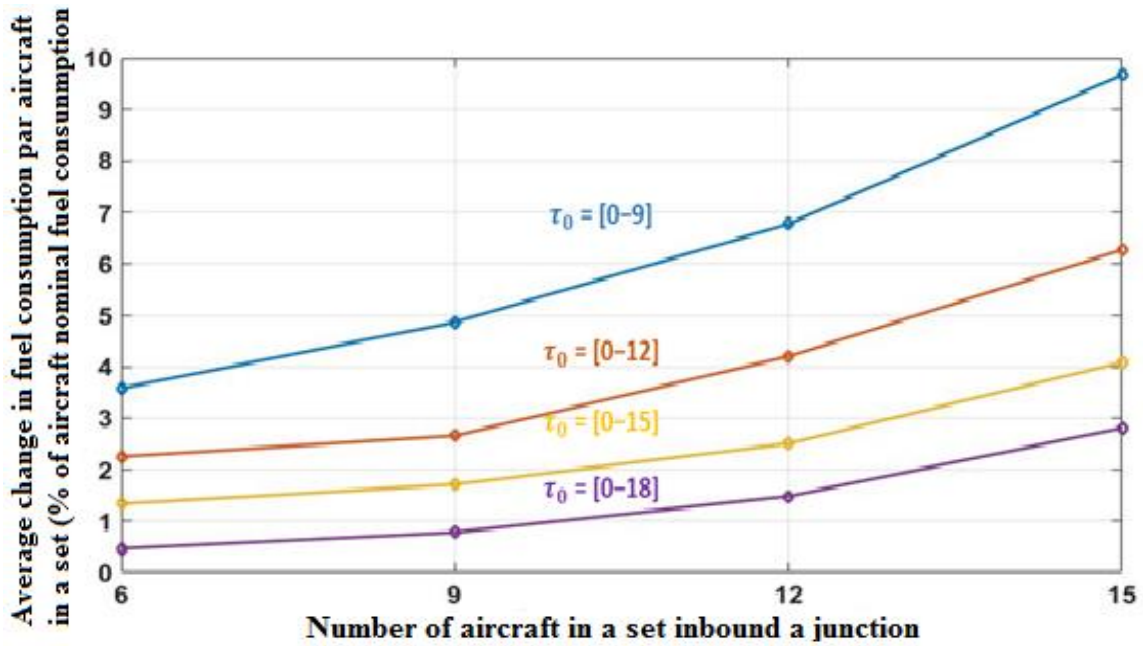


Figure 65: Excess fuel consumption due to speed/TOA changes

As it can be seen in **Figure 65**, for τ_0 intervals greater than $[0, 9]$, the average change in fuel consumption is below 6% for all aircraft sets considered. When τ_0 is $[0, 9]$, the changes are above 6% and below 10% for 12 A/C and 15 A/C in a set, while for τ_0 of $[0, 18]$, the changes are below 3% for all aircraft sets considered. These results show that for instance, when τ_0 is $[0, 9]$, to resolve conflicts involving six-aircraft inbound a

junction in an hour (corresponding to a probability of aircraft simultaneous arrival at junction of 10^{-5}); an average change of 3.5% in fuel consumption for a typical A320 aircraft is required.

7 IMPLEMENTATION OF OPTIMISED TOA ADJUSTMENTS IN ECAC TRAFFIC NETWORK

7.1 Case Study of Main Air Traffic Network

As discussed in Section 5.1.2 and generally acknowledged in the literature [14], air traffic density is correlated to Air Traffic Control (ATC) workload associated to Air Traffic Controllers' (ATCOs') tactical interventions in dealing with conflicts. Given the European Civil Aviation Conference (ECAC) is one of the busiest airspaces in the world, a high-density traffic scenario of the whole ECAC air traffic-network is considered for implementation exercises of the optimised Times of Arrival (TOAs) adjustments. As discussed in Section 2.4.1, ECAC airspace is a geographic area covering all the ECAC member states. Detailed geographical coordinates defining the actual volume of ECAC airspace are provided in Appendix B.

The Performance of proposed Air Traffic Flow and Capacity Management (ATFCM) Demand and Capacity Balancing (DCB) method in this environment is considered relevant to demonstrate its feasibility and to verify its potential acceptability by Air Traffic Management (ATM) stakeholders.

The developed ECAC traffic network scenario is supported by Flight Plan (FPL) data, extracted from EUROCONTROL Demand Data Repository 2 (DDR2) (see Section 3.6). Approximately one week after the end of each Aeronautical Information Regulation And Control (AIRAC) cycle [135], EUROCONTROL generates a 28-day long dataset file of the whole ECAC air traffic. This dataset is stored on DDR2 server in SO6 files format. This air traffic dataset, commonly referred to as the "AIRAC cycle dataset", contains three types of aircraft trajectory data [135]:

1. ***Planned flight trajectory (FTFM) data***: Which contains all the aircraft last filled FPLs before any ATFCM regulation is put in place. These FPLs represent the Airspace Users' (AUs') preferred trajectories. This type of data is provided in a data file called SO6 M1 in EUROCONTROL Network Strategic Tool (NEST) terminology;

2. **Regulated flight trajectory (RTFM) data:** Contains all aircraft FPLs updated according to the ATFCM regulations in place, such that, each delayed aircraft have a FPL equivalent to its planned FPL with a constant time offset corresponding to the imposed delay, while each re-routed aircraft have a totally new FPL. This type of data is provided in a data file called SO6 M2 in NEST terminology;
3. **Actual flight trajectory (CTFM) data:** This contains all the actual flown trajectories. These trajectories represent the closest estimate of the flight trajectories handled by ATCOs on the day of operations. This type of data is provided in a data file called SO6 M3 in NEST terminology.

According to EUROCONTROL [15], the air traffic in ECAC reached an all-time record of 10,190,903 flights in 2016, with a daily average traffic of 27,844 flights, surpassing the former record set in 2008. The busiest day of the year was on Friday, 9 September 2016, with 34,594 flights. However, these EUROCONTROL records are based on the actual flight trajectories (CTFM or M3 file). Since the proposed ATFCM DCB method is considered at pre-flight phase, this thesis investigates DDR2 planned flight trajectories (FTFM or M1 file) to re-analyse the traffic distribution for the month of September 2016. Nevertheless, Friday 9 September 2016 remains the busiest day of the year with 35,703 planned flights recorded, as shown in **Figure 66**.

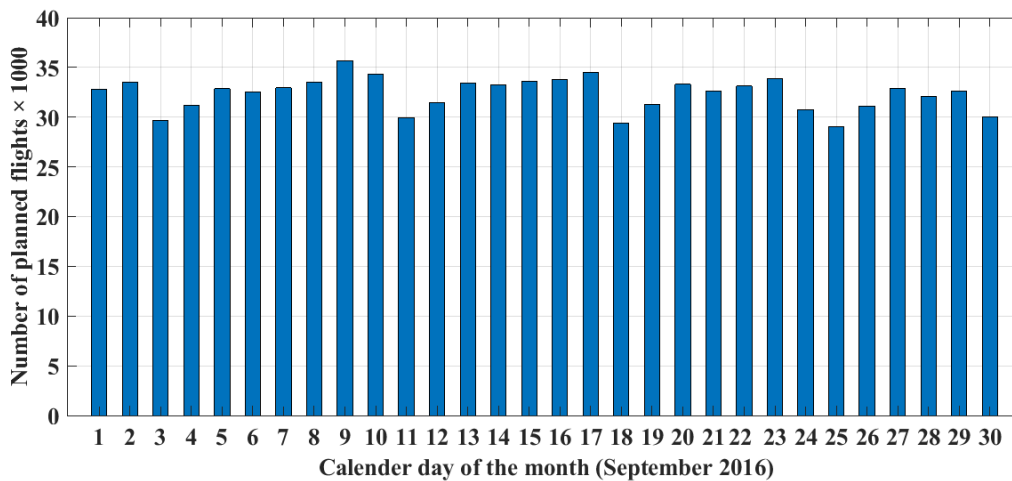


Figure 66: Distribution of planned flight trajectories per day for September 2016 in ECAC area

This busiest day of the year (9 September 2016), had the most peak 30-minute time window between 8:00 a.m. and 8:30 a.m. GMT with 1169 planned flights recorded. Since the proposed ATFCM method is considered as a Short-Term ATFCM measure (STAM) and given that STAM is applied to a limited number of flights in the network (as defined in Section 2.7.3), the planned traffic in this time window is selected for the first set of testing and analysis discussed in this chapter. However, for each planned flight in this time window, its whole trajectory in the ECAC airspace is considered for conflict identification and TOA adjustment. **Figure 67** shows the planned trajectories of all flights in ECAC airspace on 9 September 2016 from 8.00 a.m. to 8.30 a.m. GMT (the selected time window).

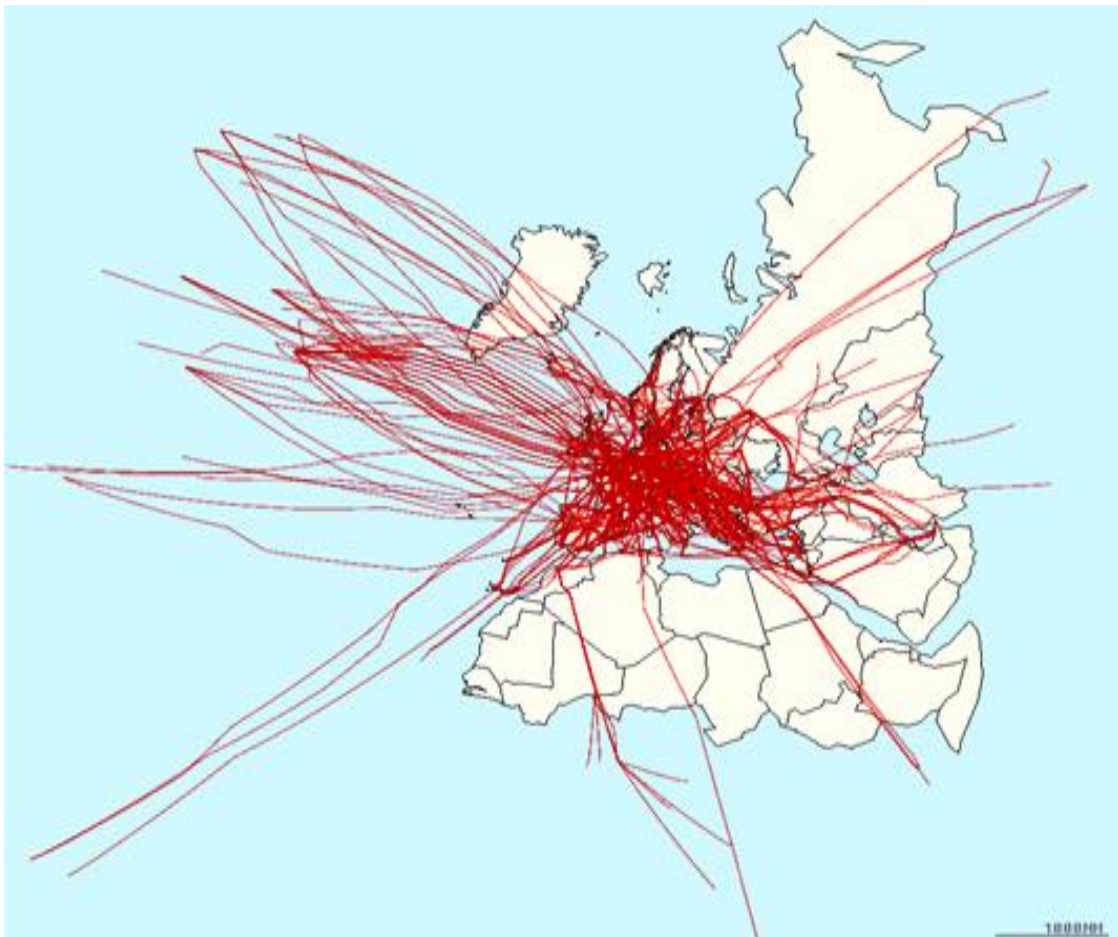


Figure 67: Planned trajectories of all flights in ECAC area between 8:00 a.m. to 8:30 a.m. GMT on 9th September 2016

Each planned trajectory in DDR2 is provided as a time set of route segments, defined by detailed information including the flight distance, flight time and flight speed of each

segment. This enables the analysis to derive all the input parameters required by the proposed LP optimisation model to compute the required optimal TOA/ speed changes to remove conflicts at junctions. **Figure 68** shows a summary of the parameters contained in each segment of the DDR2 planned trajectory data, while a detailed data sample of DDR2 planned trajectories is described in Appendix C.

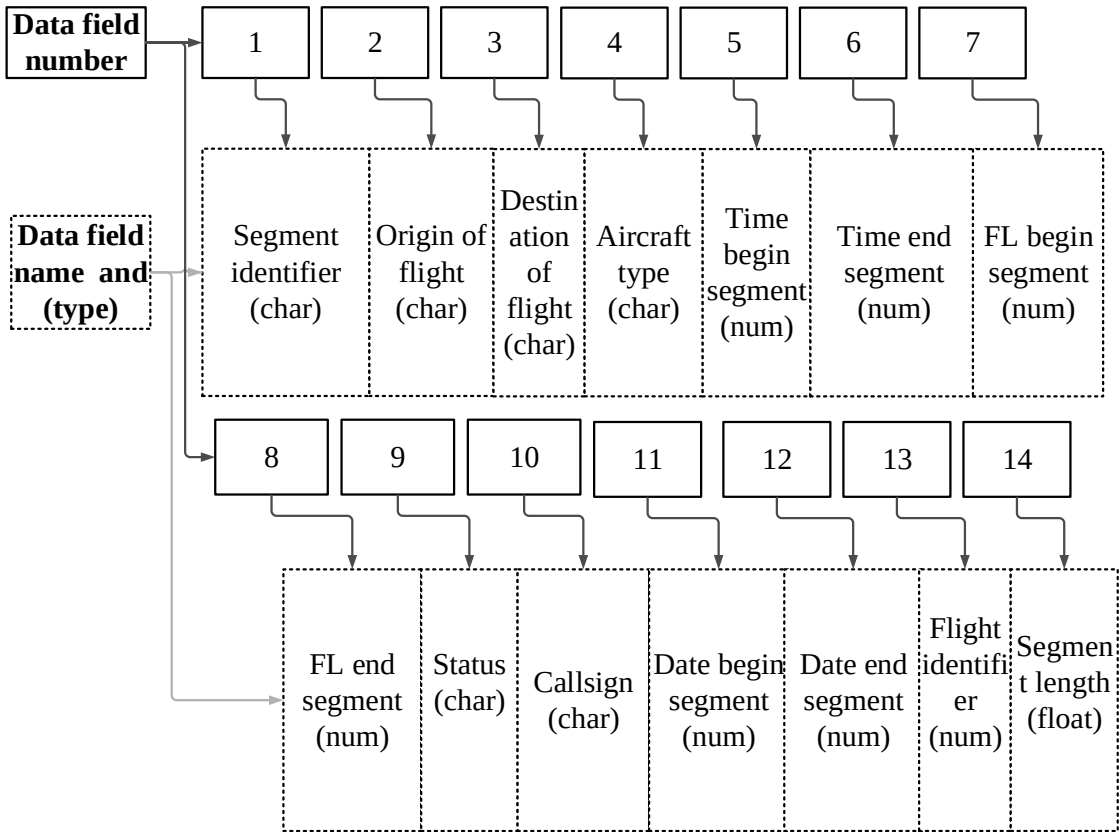


Figure 68: Summary of parameters contained in DDR2 planned trajectory data

7.2 Identification of Conflicts in the Traffic Sample

As discussed in Section 3.6, NEST is used to detect and analyse all conflicts in all considered ECAC planned traffic samples. The conflict analysis tool in NEST identifies and provides detailed information of conflicts, including their location and the encounter angle required to identify and characterise all active junctions (hotspots) in the network. **Figure 69** depicts a summarised description of the information provided for each identified conflict data in NEST. A detailed data sample of conflicts detected can be seen in Appendix D.

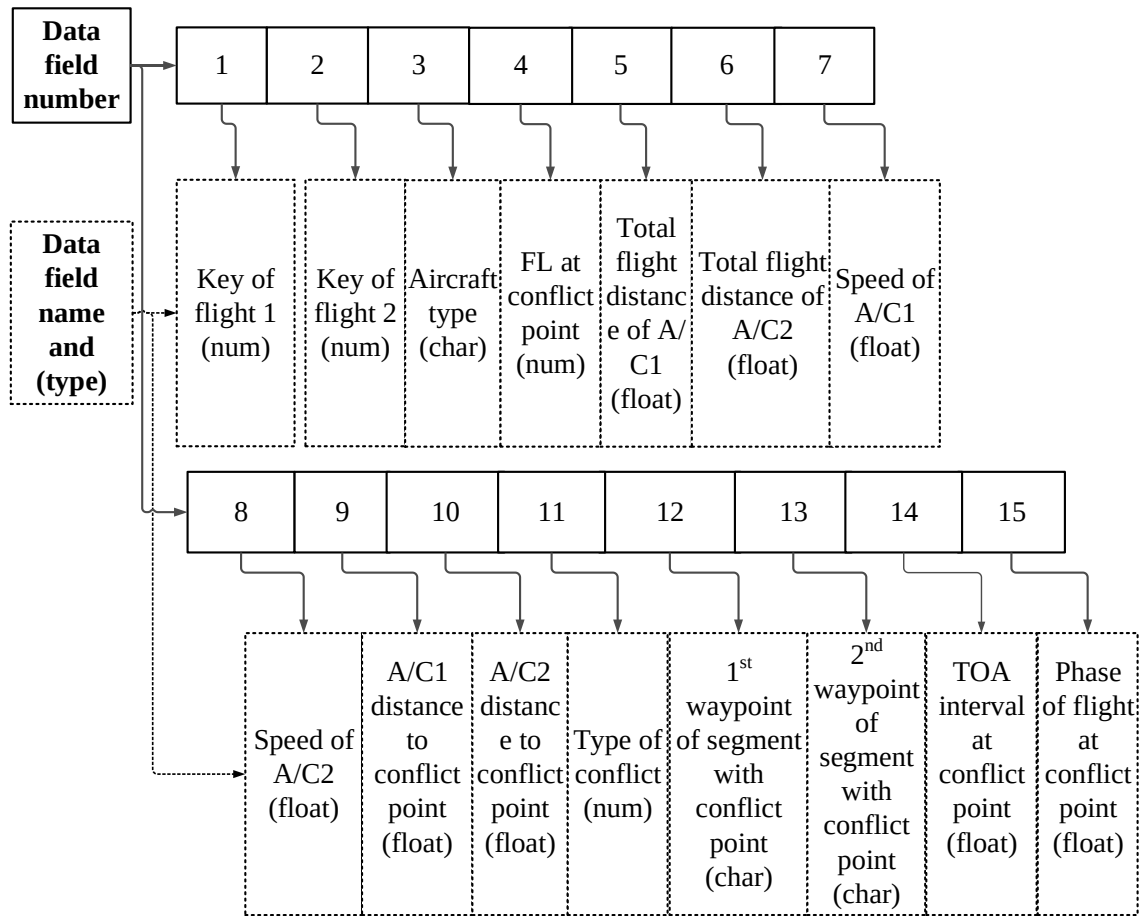


Figure 69: Data information provided in NEST for each identified conflict

As stated in the assumptions made in Section 5.1.3, parallel and opposite type of conflicts are not considered. In addition, since Terminal Manoeuvring Areas (TMAs) are considered as boundary condition of the problem and given that evolving type of conflicts are usually predominant in this part of the air traffic network, they are also initially not included in the analysis. However, the effect of evolving conflicts on the implementation of TOA/speed adjustment is discussed in Section 7.4.2.

To this end, crossing and merging conflicts involving aircraft in cruise flight beyond the limits of all ECAC's TMAs' borders are considered for conflict removal. Consequently, the Reduced Vertical Separation Minima (RVSM) rule of 1000 feet vertical separation at Flight Levels (FLs) FL290 - FL410 inclusive, and the 5 NM horizontal separation minimum applied in ECAC en-route airspace are used for conflict identification.

Figure 70 shows the total number of conflicts detected on the right y-axis (red line chart) and the distribution of number of cruise crossing and merging type of conflicts in percentage of total conflicts detected on the left y-axis (blue bar charts), considering different minimum FLs.

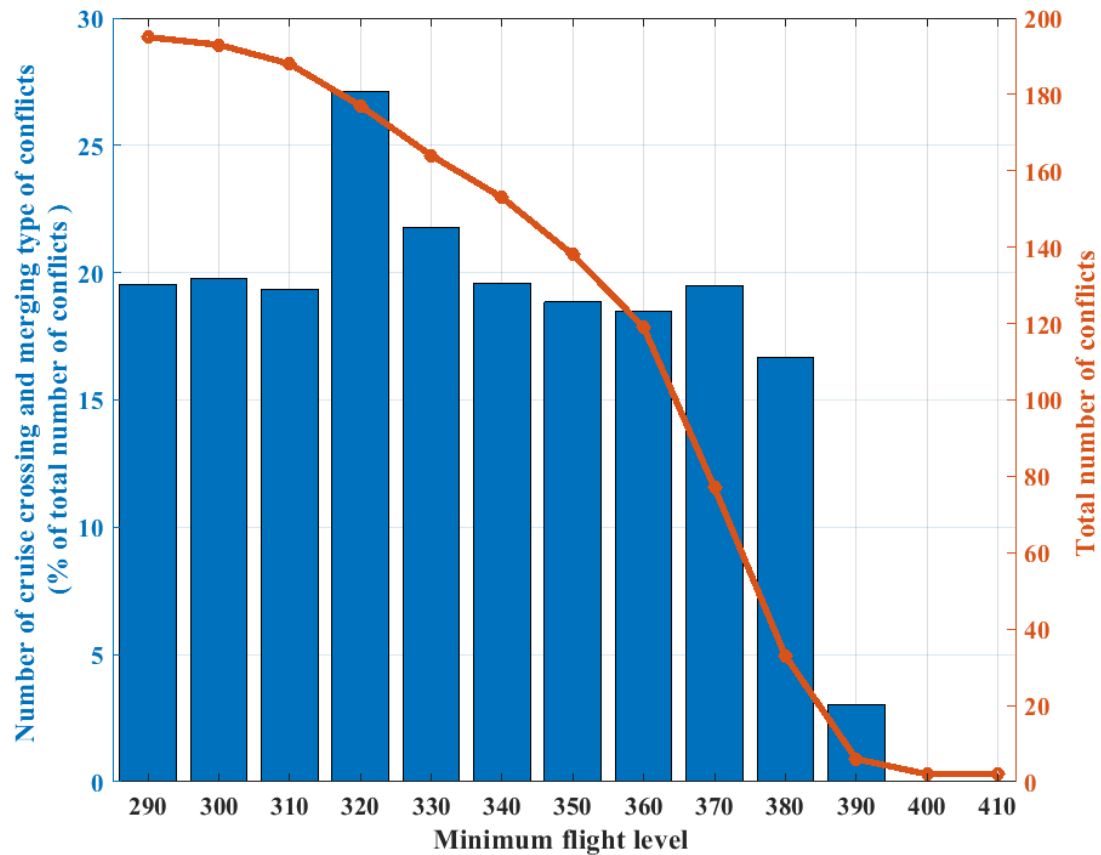


Figure 70: Total number of conflicts (red line chart) and distribution of number of cruise crossing and merging type of conflicts at and above different minimum flight-levels (blue bar charts)

In **Figure 70**, although high numbers of total conflicts detected at low minimum FLs (FL290 - FL380) can be attributed to high numbers of flights flying at these FLs, they are also attributed to the conflicts between evolving aircraft in climb/descent flights to/from different TMAs in ECAC airspace and aircraft already established in the cruise flight. The number of aircraft that fly at very high FLs (FL390- FL410) within ECAC airspace is very low and exhibiting predominantly parallel conflicts in cruise flights.

As also shown in **Figure 70**, the number of cruise crossing and merging conflicts is highest at FL320 with 27.12% of the total 177 conflicts detected at this minimum FL (equivalent to 48 conflicts). Therefore, given that this thesis mainly concerns solving this type of conflicts, the identified aircraft involved in cruise crossing and merging conflicts at and above FL320 are chosen to be the subject of TOA/speed changes for conflict removal. These 48 detected conflicts involve 86 aircraft of which 77 aircraft have a single active junction, 8 aircraft have two active junctions along their trajectories and 1 aircraft have three active junctions along its trajectory.

7.3 Implementation of TOA Adjustments for Conflict Removal in ECAC Traffic Network with $P_c = 10^{-5}$

To implement TOA adjustment for conflict removal in the considered ECAC traffic network scenario, a probability value of aircraft simultaneous arrival at junction of 10^{-5} ($P_c=10^{-5}$) is set. This probability value is considered low enough to reduce significantly the current ATC workload in ECAC area, associated to actual ATCOs' tactical interventions, assuming that each detected conflict would result into ATC tactical intervention if no action is taken at pre-flight phase. As already established in Chapter 6, if $P_c=10^{-5}$ is set as the target, a minimum TOA interval between any two consecutive aircraft at any active junction of 9.4 minutes must be achieved in order to remove all conflicts detected in the scenario.

The LP optimisation model is applied to obtain the optimal speed changes before and after each active junction for each aircraft identified in conflict(s) to achieve the above-required minimum TOA interval at each junction, for all 48 identified conflicts. The optimal speed changes applied before the aircraft reach the active junctions are required to remove the conflicts for all aircraft, whilst the optimal speed changes after the active junctions are required to maintain the TTA at destination in the case of aircraft with a single active junction along trajectory. For aircraft with multiple active junctions along the trajectory, speed changes are applied for each trajectory segment that is before and after each relevant active junction to remove the conflicts at each of these multiple

junctions, and speed changes are applied to the trajectory segment after the last active junction to maintain the TTA of each aircraft at its destination.

Figure 71 shows the computed pair of optimal speed changes before and after each junction for each aircraft per each conflict, in percentage of nominal aircraft speed. All the computed required optimal speed changes ranges between $[-8.9\%, +9.1\%]$ of the nominal aircraft speed, with only 16.7% of the total speed change instances above $\pm 6\%$ speed change range, 83.3% of total speed change instances are within $\pm 6\%$ speed change range and 19.8% of total speed change instances within $\pm 3\%$ speed change range. As discussed later in Section 7.4.1, the speed changes in the above speed change ranges can be implemented by the aircraft to resolve conflicts without affecting the ATCOs traffic situation awareness.

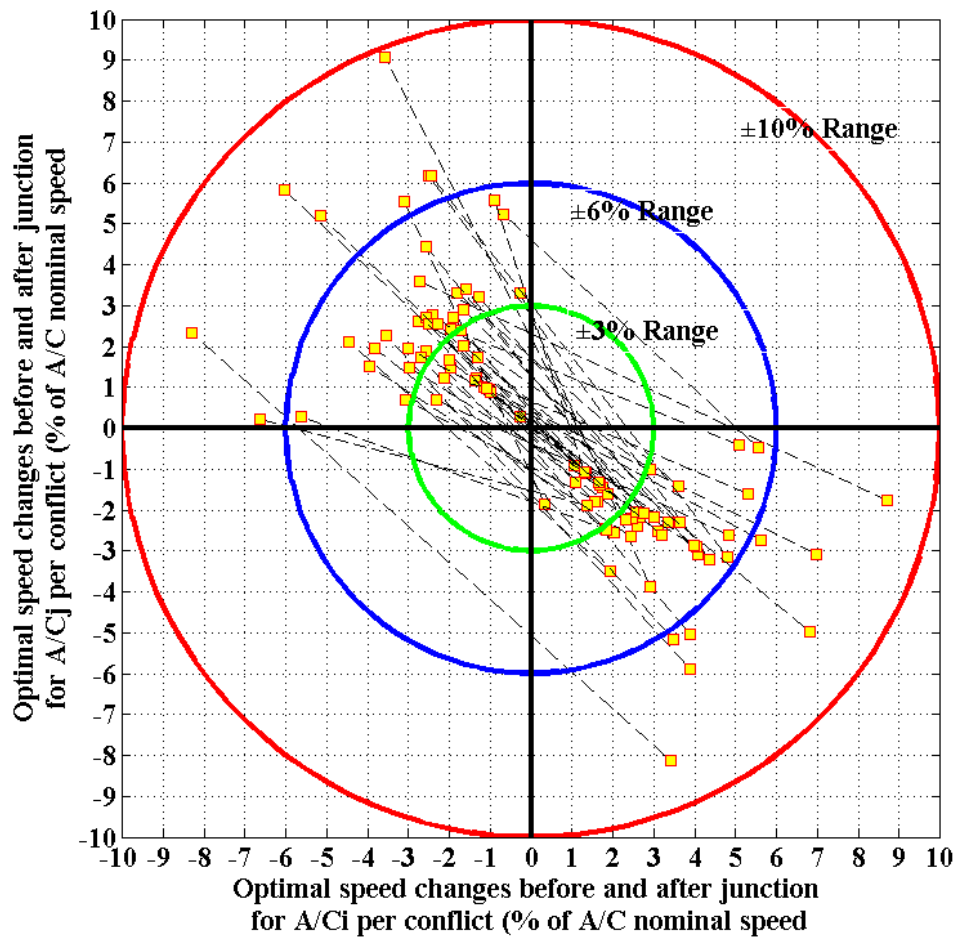


Figure 71: Computed optimal speed changes before and after junction per each identified conflict for each A/Ci and A/Cj

To test the performance of the proposed ATFCM DCB method, the computed optimal speed changes shown in **Figure 71** are applied to the aircraft nominal flight speed profiles in the initial FPLs of all the 86 aircraft involved in the conflicts. These new FPLs are then introduced back into the same ECAC traffic network sample including non-conflicted aircraft. The resulting scenario containing all the 1169 flights is re-analysed using the NEST conflict detection tool where all the 48 cruise crossing and merging conflicts involving all conflicted 86 aircraft with TOA/Speed adjustments are successfully removed. This solution results into three induced conflicts (conflicts caused by the solution to aircraft that were not initially considered for speed/TOA changes). However, when the scenario is re-analysed with TOA/speed adjustments applied also to aircraft involved in induced conflicts, this cascading effect is removed.

In conclusion, by applying optimal TOA/speed adjustments at pre-flight phase, all the cruise crossing and merging conflicts (48 conflicts) among aircraft flying at FL320 and above in ECAC airspace between 8:00 am - 8:30 am on 9 September 2017 are removed. The proposed method, therefore, provides the expected results as it removes all conflicts considered in scope of the solution. In addition, as linear programming is applied, the average time to obtain the results is approximately 4 seconds when estimated from 10 executions. Hence, the execution time should not be a limiting factor even for increased higher-densities of air traffic expected in ECAC airspace in the future when TBO is to be implemented (See Section 7.4.3 for a forecasted scenario).

7.4 Feasibility of Proposed ATFCM DCB Method

7.4.1 Feasibility from Air Traffic Controller and Airspace User Perspectives

Although the results discussed in previous section shows the possibility of aircraft pre-flight de-confliction by TOA/Speed changes, the proposed ATCM DCB method can be adopted only if the computed speed/TOA changes are realistic and practical from both ATCO daily operations and AU perspectives.

Concerning the ATCO operations, previous studies based on results obtained using Fast Time Simulations (FTS) tools have concluded that aircraft speed modifications within a range of $\pm 10\%$ of their nominal speeds, could be applied without being noticed by the

ATCO [31]. The optimal speed changes computed in this thesis are all below this range. In addition, Human in the Loop (HIL) experiments have shown that speed changes in the range of $\pm 6\%$ were not noticed by ATCOs even though the ATCOs were informed of the ongoing covert speed change experiment[130]. In this thesis, 83.3% of the computed required optimal speed changes are within $\pm 6\%$ speed change range. Furthermore, in the above HIL experiments, it was also concluded that even for greater speed changes of up to $\pm 12\%$, ATCOs still did not notice 50% of them. The main observation from the above experiments was that, for en-route flights, the absolute values of the aircraft speed changes are only sporadically considered and memorized by ATCOs.

Based on the above references, the speed changes computed in this thesis can be introduced in the FPLs and implemented by the aircraft while keeping out the ATCO situational awareness from the ongoing conflict resolution process. This resolution process can then be conceived in such a way that it can be considered at pre-flight level and can be integrated into tactical ATC procedures to reduce the current ATC tactical interventions.

The speed changes obtained in 7.3, are computed to achieve the required probability of aircraft simultaneous arrival at junction (P_C) value of 10^{-5} with the requirement of a minimum time interval of approximately $\tau_p = 9.4$ minutes between consecutive aircraft at junction. The maximum inbound traffic flow at the junction (the frequency of traffic) is then limited to approximately $QI_m = 1/\tau_p = 6$ aircraft/hour. On aggregate level therefore, this probability determines the maximum number of aircraft throughput for a given airspace volume which affects the ATCO workload per flight, and in turn, largely determines the airspace capacity/ATC resources availability. Based on this rationale, depending on the available ATC workforce, different P_C values can be used to remove the expected conflicts.

With the identification of conflicts basing on the conventional en-route separation minima (5 NM lateral and 1000 feet vertical) and with no mitigation action taken at pre-flight phase, it can then be realistically assumed that ATC tactical interventions are very likely for each of the 48 conflicts identified in Section 7.2. Therefore, even by

increasing the P_C value from 10^{-5} to higher values, the resulting lower speed/TOA changes will still significantly reduce the current probability of ATC Separation Management (SM) tactical interventions.

Figure 72 shows the required optimal speed changes before and after an active junction for different aircraft at the 48 identified active junctions, computed at various P_C values. The graph shows that when the P_C value increases, the required speed changes considerably reduce. For instance, the worst case at P_C value of 10^{-5} is 9.1% speeding up (the highest percentage of all computed speed changes at $P_C = 10^{-5}$ in **Figure 72**). This value decreases to 7% and subsequently to 5.4%, 4.1% and 3.2% when P_C increases from 10^{-5} to 10^{-4} and subsequently to 10^{-3} , 10^{-2} and 10^{-1} respectively. This is equivalent to a reduction of speed changes by a factor of 1.3% when P_C is increased by a factor of 10; and this trend applies to all computed speed changes.

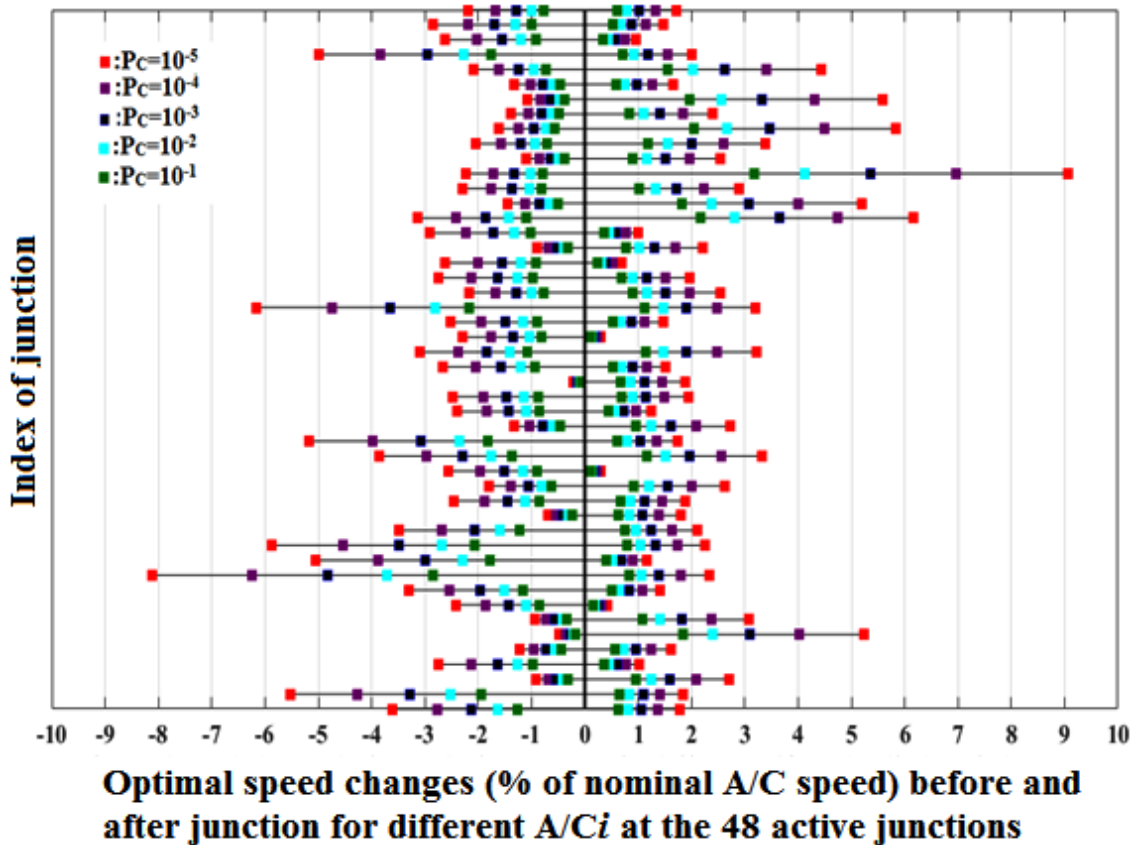


Figure 72: Optimal speed changes before and after an active junction for different A/Ci at the 48 identified active junctions for different required probabilities of aircraft simultaneous arrival to the junction

From the results shown in **Figure 72**, depending on the required P_C value, the amount of speed/TOA changes required to remove conflicts is significantly different, but all could result in the reduction of the current ATC tactical interventions.

From the AU perspective, if the computed optimal TOA/speed changes do not significantly affect the aircraft performance, hence not significantly affecting direct flight operating costs, they are likely to be accepted as the constraints in the RBTs. When high speed/TOA changes are required, especially when they are computed at very low P_C values, other ATFCM measures may be applied to complement the proposed ATFCM DCB method to reduce the required speed/TOA changes to lower values. Moreover, as previously discussed in Section 5.1, the proposed ATFCM DCB method is not expected to be a distinctive technique to produce a conflict free airspace. Instead, other collaborative and coordinated actions should be applied simultaneously with it.

Aligned with this context, another STAM measure the “cooPerative depArtuRes for a compeTitive ATM networK sErvice (PARTAKE)”[149], a project under SESAR 2020 Exploratory Research programme can be used to complement the proposed ATFCM DCB measure. PARTAKE introduces an improvement in the air traffic dynamic demand and capacity balancing by prompt identification of conflicts at network level, and re-adjusting the Estimated Take-Off Times (ETOTs) of affected aircraft within their assigned nominal Calculated Take-Off Time (CTOT) margins, and rearranging the departing sequence at the involved airports to remove those conflicts.

The ATFCM DCB method proposed in this thesis and the PARTAKE approach are somehow complementary. That is, if the computed TOA adjustments at junctions for certain conflicts require speed changes that are not practical, the solution from PARTAKE can help-by adjusting the aircraft ETOTS in such a way that just smaller TOA adjustments at junction are required, hence, minimising the required speed changes to remove those conflicts. Similarly, if the PARTAKE solution cannot find feasible new take-off times within the assigned nominal CTOT margins to remove certain conflicts, the proposed ATFCM DCB measure could be introduced to provide new TOA adjustments at junctions to enhance the solution. This complimentary

solution could help to preserve aircraft CTOT and TTA while removing the conflicts at ECAC network level.

7.4.2 Consideration of Cruise-Evolving Type of Conflicts

The scenario discussed so far has only considered conflicts from crossing and merging aircraft flying in cruise phase. However, there is a significant amount of separation infringements caused by climbing/descending aircraft to/from different TMAs in ECAC airspace that cross the trajectories of safely separated aircraft flying in cruise phase, disturbing a seamless air traffic flow. This type of conflicts is commonly referred to as cruise-evolving crossing conflict. To discuss its impact, a scenario combining both cruise crossing and merging conflicts and cruise-evolving crossing conflicts is simulated and analysed, following the same process of conflict identification and TOA/speed changes implementation described in Section 7.2 and Section 7.3. This new scenario demonstrates the approach capability to remove also the cruise-evolving crossing type of conflicts.

Figure 73 shows the total number of conflicts identified, denoted by the red graph on the right y-axis. The left y-axis shows the distribution of the number of cruise-evolving crossing conflicts (light blue bars), distribution of the number of cruise crossing and merging conflicts (blue bars) as well as the distribution of the number of cruise crossing and merging conflicts + cruise-evolving crossing conflicts (grey bars), represented in percentage of total conflicts identified at and above different minimum FLs. It can be seen in **Figure 73**, that cruise-evolving crossing conflicts are only detected at and above low minimum FLs (290-360). This is due to low number of evolving aircraft climbing to or descending from different TMAs in ECAC area at higher FLs.

The highest percentage of cruise crossing and merging conflicts + cruise-evolving crossing conflicts is detected at FL320 accounting for 36.16% (64 conflicts) of the total 177 conflicts detected. From this percentage, 9.04% (16 conflicts) are cruise-evolving crossing conflicts and 27.12% (48 conflicts) are cruise crossing and merging conflicts.

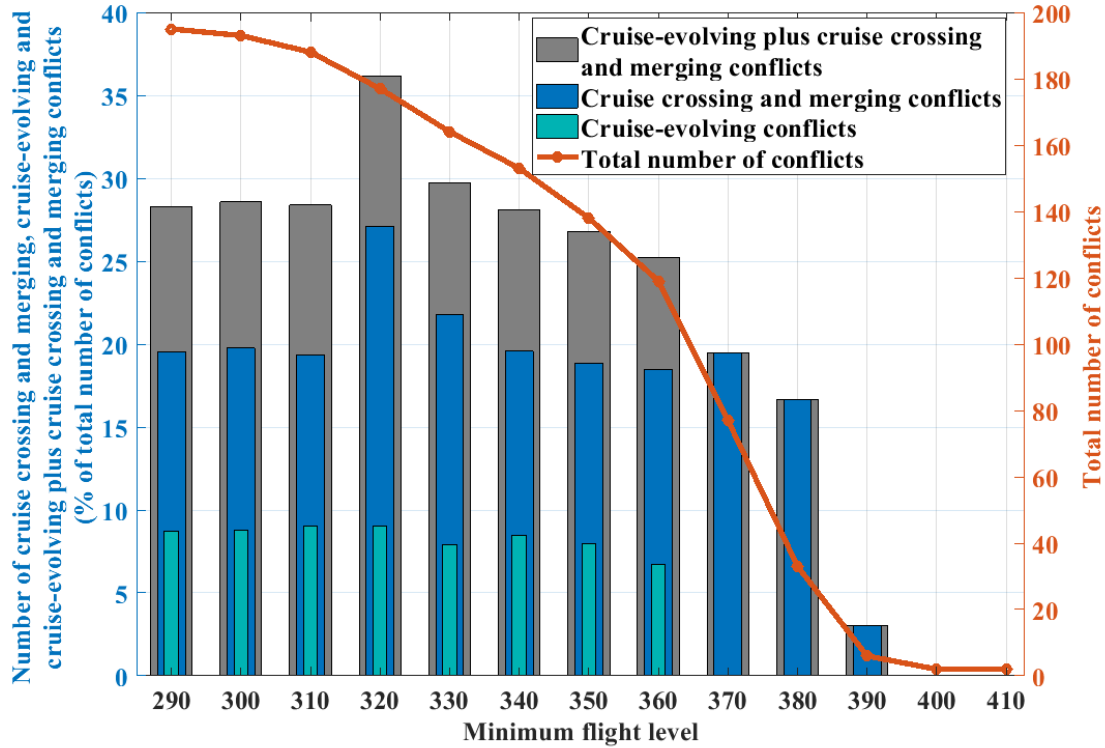


Figure 73: Total number of conflicts (red line chart) and distribution of number of cruise crossing and merging, cruise-evolving and cruise-evolving plus cruise crossing and merging conflicts at and above different minimum flight-levels (bar charts)

Figure 74 shows the computed optimal speed changes required before and after junction per each conflict for each aircraft pair (A/C_i and A/C_j) for all 64 identified cruise crossing and merging conflicts + cruise-evolving crossing conflicts. The yellow box markers show the speed changes required to remove the cruise crossing and merging conflicts whilst red box markers show the speed changes required to remove the cruise-evolving crossing conflicts. Similar to the scenario in Section 7.3, all the speed changes are computed to achieve a P_C value of 10^{-5} .

Comparing the results in **Figure 74** to the results in **Figure 71** that were obtained without considering the cruise-evolving crossing conflicts, the range of the required optimal speed changes has increased from $[-8.9\%, 9.1\%]$ to $[-13.1\%, 14\%]$ when the cruise-evolving crossing conflicts are considered. In addition, when cruise-evolving crossing conflicts are not considered (see **Figure 71**), all computed optimal speed

changes are well below $\pm 10\%$ ²². When cruise-evolving crossing conflicts are considered as shown in **Figure 74**, 6.25 % of the computed optimal speed changes are above $\pm 10\%$ speed change range threshold. The high-speed changes required to remove some cruise-evolving crossing conflicts are mainly attributed to short anticipation time/flight distance before the active junction that is available for some evolving aircraft.

For those aircraft with short anticipation time before the active junction, the proposed ATFCM method should be applied together with other collaborative and coordinated ATFCM measures such as PARTAKE as suggested in Section 7.4.1. Alternatively, lower speed changes could be computed at higher P_C values. For instance, increasing P_C value to 10^{-4} for the same scenario results in approximately 1.6% of the required optimal speed changes above $\pm 10\%$ threshold as shown in **Figure 75**, much lower than 6.25% obtained in **Figure 74** when $P_C = 10^{-5}$.

²² The 10% threshold was established in Section 7.4.1 as the limit at which speed modifications are not noticeable by the ATCOs.

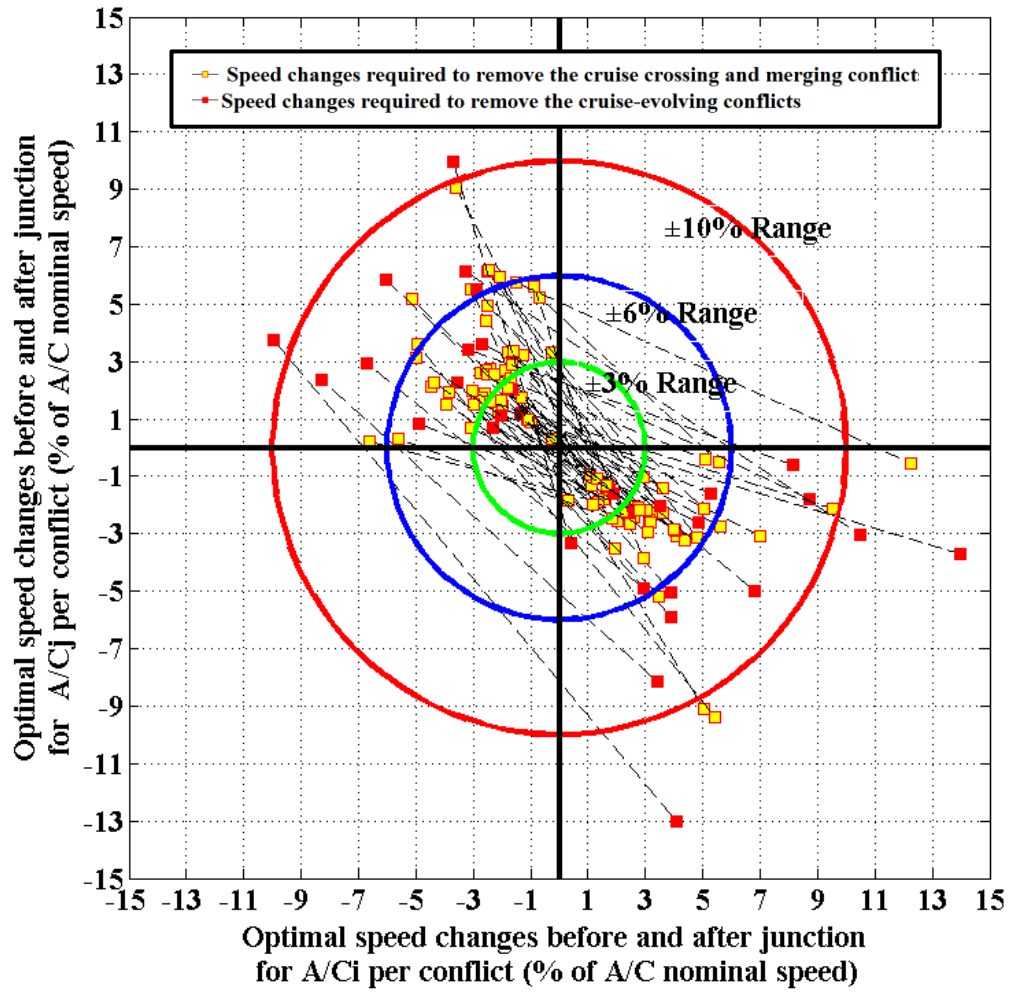


Figure 74: Computed optimal speed changes before and after junction per each identified conflict for A/Ci and A/Cj considering cruise crossing and merging conflict plus cruise-evolving conflicts at $P_C=10^{-5}$

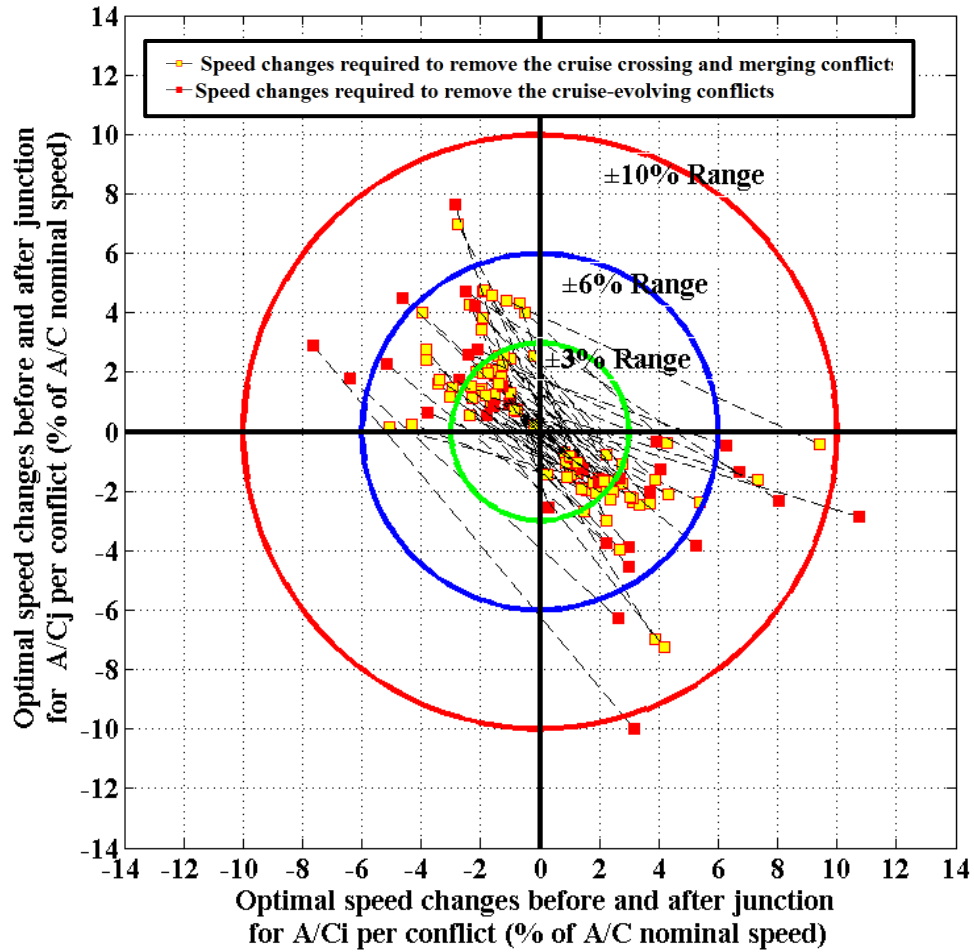


Figure 75: Computed optimal speed changes before and after junction per identified conflict for A/Ci and A/Cj considering cruise crossing and merging conflicts plus cruise-evolving conflicts scenario at $P_C=10^{-4}$

7.4.3 Implementation of Optimised TOA Changes in ECAC Mid-Term Forecasted Traffic Scenario

Since the proposed ATFCM DCB measure is based on TBO which is expected to be implemented in the ATM system in the mid-term to long-term future, it is necessary to analyse the feasibility of this measure in the operational environment considering forecasted traffic scenario. As discussed in Section 3.6, this thesis uses a forecasted traffic scenario produced using NEST forecast modelling tool and EUROCONTROL Statistics and Forecast Service (STATFOR) MTF model inputs. The DDR2 historical traffic sample for the whole most peak day (9 September 2016) in ECAC airspace that is also used for scenarios discussed in Section 7.1 is selected as the baseline. This baseline scenario consist data for planned trajectories that is “cloned” to generate the

forecasted traffic. This forecasted traffic is generated in the same data format same as that of the planned trajectories in the baseline scenario described in **Figure 68**. The result is an estimate of traffic in ECAC airspace on 9 September 2022 (6 years forecast) from which, traffic of the most peak 30-minute time window (8:00 am - 8:30 am GMT) is extracted and used for the TOA feasibility analysis.

The NEST forecast-modelling tool has been used mainly because it maintains the integrity and consistency of the data format of traffic in the forecasted traffic scenario. The traffic forecast generation process in NEST is illustrated in **Figure 76**, where the inputs applied in this thesis to generate the forecast are highlighted in blue. As illustrated in **Figure 76**, the STATFOR MTF forecasting option (6 year forecast), the STATFOR “High” growth trend, and the “Constrained” airport capacity options are applied to generate the future traffic sample for year 2022. The STATFOR “High” growth trend corresponds to an assumption of strong economic growth and increasing globalisation and resource availability, enhanced by technology.

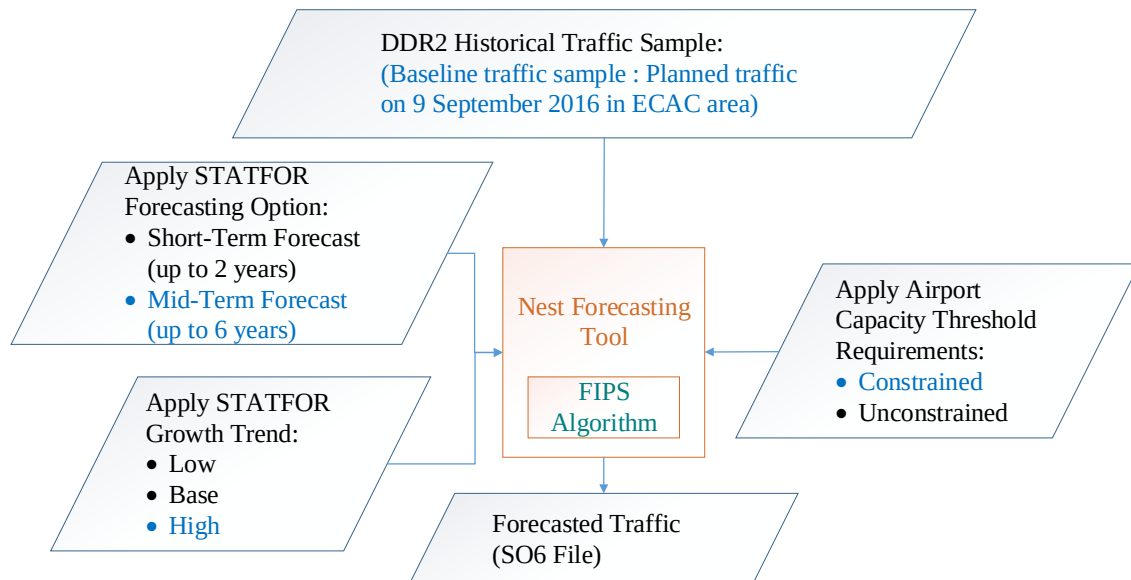


Figure 76: NEST traffic forecasting process and inputs

In the NEST modelling tool, given a set of applied inputs, traffic forecast is initially generated in terms of percentage increase in flight count with respect to the baseline traffic scenario. This percentage in flight count is then converted into detailed flight information of the forecasted traffic through a random flight cloning process, achieved

by the Flight Increase Process (FIPS) algorithm [135]. The FIPS algorithm uses a baseline traffic sample to convert traffic into future traffic samples by randomly selecting model flights from the baseline sample for cloning. A model flight is cloned by adding a random offset in its ETOT, selected between a default “-ETOT random offset max = -15 minutes” and “+ETOT random offset max = 15 minutes”. If the flight cannot be accommodated at the cloned ETOT due to the airport capacity constraints, an offset step, “ETOT offset step = ± 60 minutes”, is selected. The process is repeated until an “ETOT offset max = ± 60 minutes” is reached and then a new model flight is selected. The above ETOT offset restrictions are defined as follows:

1. ETOT random offset max: the maximum range in minutes for the randomly generated take-off time of the cloned flight;
2. ETOT offset step: the standard offset step in minutes used to calculate the new take-off time for a cloned flight;
3. ETOT offset max: the maximum offset between the model flight take-off time and the cloned flight take-off time in minutes.

For example, for a flight model with ETOT = 8:00 a.m. and an ETOT random offset of -5 minutes, the new flight is assigned to an ETOT of 7:55 a.m. If this ETOT cannot be accommodated, an ETOT offset step (“ETOT offset step = ± 60 minutes”) is then applied to compute another ETOT by randomly generating a sign (either “+” or “-”). Assuming the “+” is selected, the corresponding ETOT of 7:55 a.m. + 60 minutes = 8:45 a.m. is then assigned to the new flight. If this ETOT cannot also be accommodated by the available capacity, the FIPS alters the sign to “-” which makes 7:55 a.m. - 60 minutes = 6:45 a.m. As the ETOT offset max value has now been reached at 6:45 a.m., an alternative model flight is chosen for cloning and the process continues until a successful cloning has been achieved or failed.

Using the above process, the forecast for baseline ECAC traffic scenario on 9 September 2016 with 34,594 flights results into 44700 flights forecasted for 9 September 2022. The most peak 30-minute time window (8:00 a.m. - 8:30 a.m. GMT) of this forecasted traffic consists of 1431 flights, forecasting 262 more flights (22% increase in number of flights) compared to those in the baseline scenario.

Figure 77 provides a comparison of conflicts identified for the above time window between the baseline and the forecasted scenarios. The total number of conflicts identified for both scenarios (line charts) are shown on the right y-axis, and the distribution of number of cruise crossing and merging type of conflicts in percentage of total conflicts identified for both scenarios (bar charts) for different minimum FLs is shown on the left y-axis. It can be seen in **Figure 77** that there is an additional 83 conflicts in the 2022-forecasted traffic at and above FL320, compared to conflicts detected in 2016. This indicates an increase by approximately 47% in the number of conflicts in ECAC within a period of 6 years for the studied traffic sample. Compared to 22% forecasted increase in number of flights, the increase in number of conflicts is more than double the increase in the number of flights, suggesting a significant increase in the number of ATC SM tactical interventions required to manage the forecasted traffic. In the forecasted scenario, the identified cruise crossing and merging type of conflicts at and above FL320 consists 29.62% of the total 260 conflicts (equivalent to 77 conflicts). Therefore, there is an additional 29 cruise crossing and merging conflicts to be resolved as compared to crossing and merging conflicts in the baseline scenario.

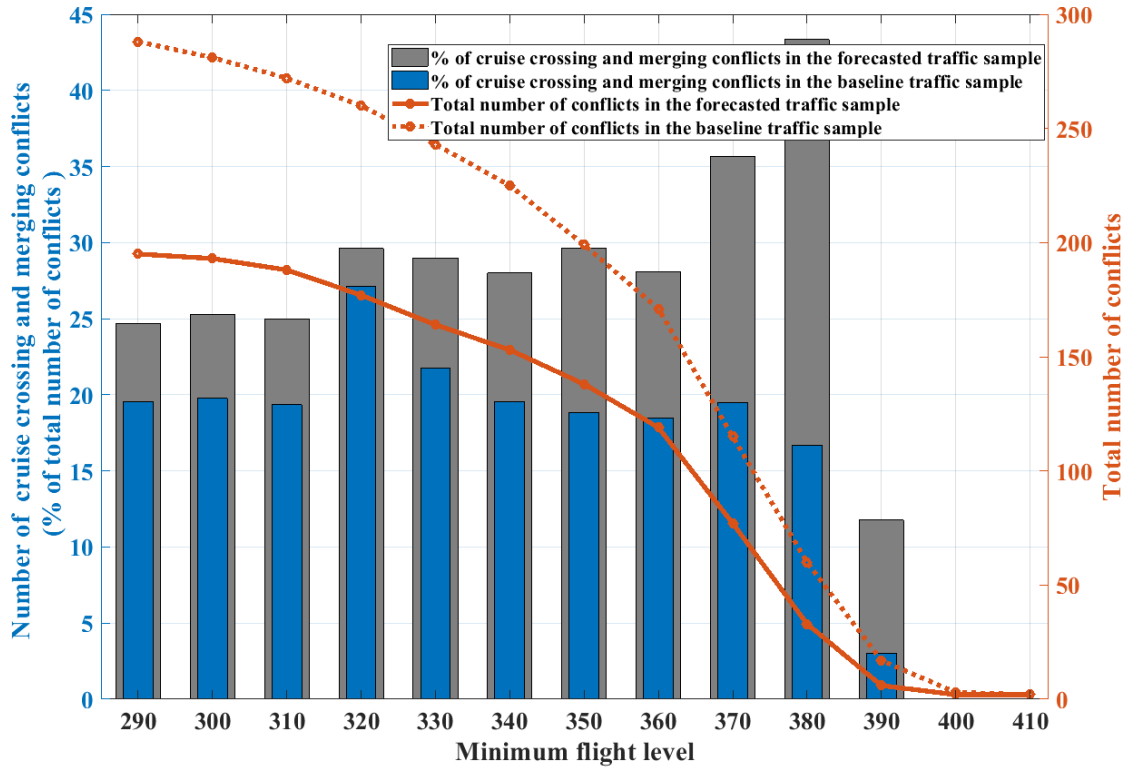


Figure 77: Comparison of total number of conflicts (right y-axis) and distribution of number of cruise-cruise crossing and merging type of conflicts at different minimum flight-levels (left y-axis) in the baseline and forecasted traffic scenarios

Figure 78 shows the required optimal speed changes (in percentage of nominal aircraft speed) before and after the junction for each identified conflict between any pair of aircraft A/C_i and A/C_j in the forecasted traffic scenario. All these optimal speed changes range between -9.1% and 9.7% of the nominal aircraft speed with 77.3% of them within $\pm 6\%$ speed change range, composed of 24.2% within $\pm 3\%$ speed change range.

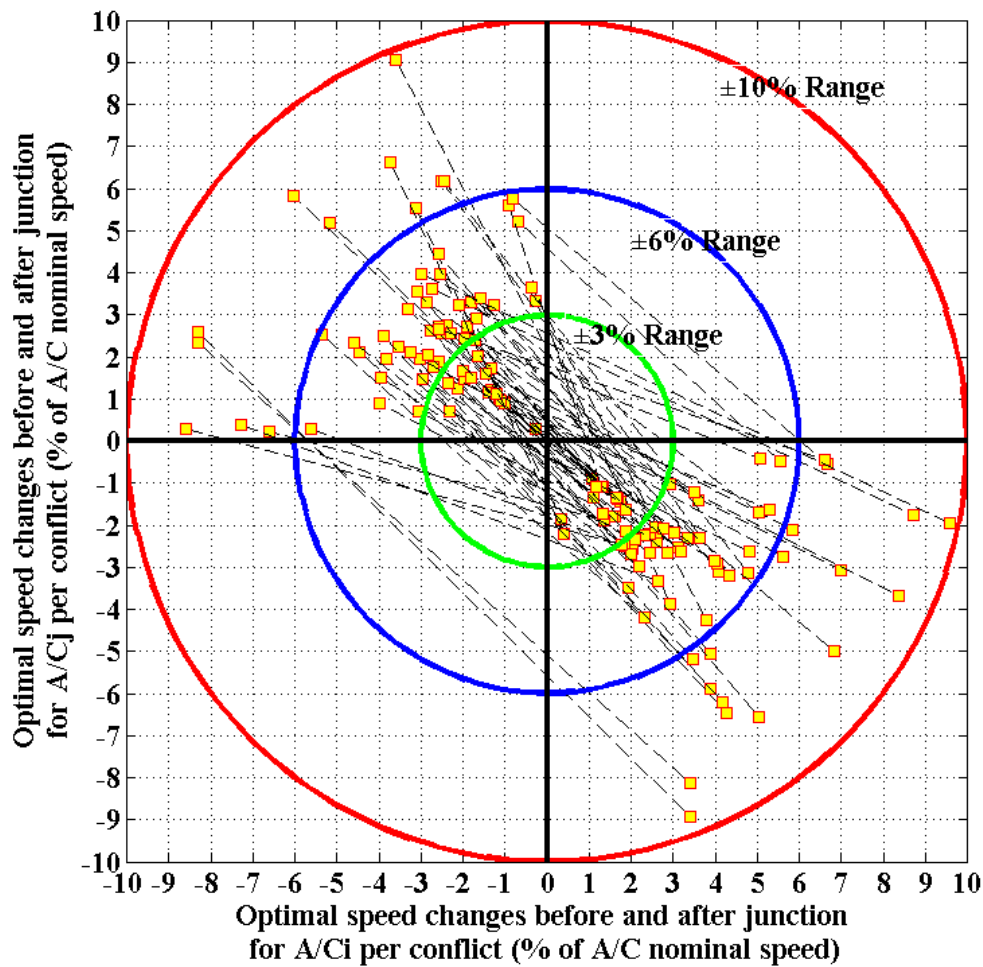


Figure 78: Computed optimal speed changes before and after junction per each identified cruise crossing and merging conflict for A/Ci and A/Cj at $P_C = 10^{-5}$ considering forecasted traffic for 2022

From these results, it can be seen that the speed changes required to remove the conflicts in the forecasted scenario have only increased slightly, compared to the speed changes required in the baseline scenario (see Section 7.3). This slight increase can be attributed to the fact that forecasted traffic is generated through a cloning process, which causes several flights in conflicts in the baseline scenario to be duplicated with the same nominal speed and flight distance before and after the active junctions. The only difference between those duplicated conflicts and their corresponding conflicts in the baseline scenario is the shift in TOAs at junction of the involved aircraft in the forecasted scenario due to new ETOTs assigned to them in the cloning process. Nevertheless, the computed optimal speed changes can still be considered the most relevant for this thesis on the basis that STATFOR MTF forecast is the current forecast

used operationally by EUROCONTROL to support the future planning of ATM system in ECAC area. In addition, the NEST modelling tool is the official tool used by the Network Manager (NM) to develop and simulate air traffic scenarios for future capacity planning in ECAC area, as discussed in Section 3.6. Therefore, the obtained results are considered sufficient to reflect the performance of the proposed ATFCM DCB method in future air traffic scenario.

7.4.4 Effect of Uncertainties on Conflict Removal

The number of conflicts removed in Section 7.3 is achieved by adjusting the nominal ground speed of the aircraft according to the computed optimal speed changes, as well as assuming that all aircraft meets their ETOT and departs on time. Therefore, this number can only be achieved by assuming an operational environment that is perfectly still where there are no factors causing variations in aircraft planned nominal ground speed and ETOT when the optimal speed changes are applied. In reality, however, the aircraft planned nominal ground speed and ETOT varies due to different uncertainties. In order to analyse the effect of uncertainties on the number of conflicts resolved by TOA adjustments, a basic exercise is performed with an assumption that uncertainties only affect and deviate the aircraft's ETOT, and that these ETOT deviations are propagated throughout the flight duration. The use of ETOT uncertainties in this analysis is supported by the fact that in the current ATFCM practices, it is universally accepted that ground delays are cheaper and safer than airborne delays [60]. Consequently, in the current operations, any foreseen delays in the system are anticipated prior to take-off at the departure airport. This makes the variations in ETOT the most significant factor in pre-flight ATFCM DCB.

In addition, in mitigating the conflicts (See Section 7.3), it was considered that aircraft operations in TMAs are boundary conditions and that these operations do not affect the solution of the proposed ATFCM DCB method. Hence, the TMA exit points were considered as the initial points of aircraft trajectories where aircraft fly out of their SIDs at exactly the planned time in their FPLs. However, since the aircraft may not always take-off on time due to the ETOT variations, there will be deviations in the arrival time

at the TMA exit points. These deviations are propagated throughout the remaining trajectory. For the sake of simplicity, they were not included in Section 7.3 analysis.

To analyse the effect of these deviations on the number of conflicts removed by the proposed method, the simulation scenario in Section 7.3 is re-run in the NEST conflict detection tool with an input of deviation on aircraft take-off time. The number of conflicts removed in Section 7.3 scenario (without considering the deviations in aircraft take-off time) is taken as the benchmark value.

In NEST conflict detection tool, aircraft take-off time deviations can be applied as inputs to all aircraft in the scenario in terms of time units of mean delay value (μ) and standard deviation value (σ) [135]. Each run of conflict detection simulation uses these values to distribute the aircraft take-off time along a Gaussian normal curve whilst detecting the resulting number of resolved conflicts. As discussed in Section 5.5, according to the EUROCONTROL Performance review Report (PRR), an average of 4.4 minutes delay per departure was registered at the top 30 busy airports in Europe in 2016. In this analysis, this value is selected as the aircraft take-off mean delay value ($\mu = 264$ seconds). An assumption of the same amount of time for the standard deviation ($\sigma = 264$ seconds) is also used. Since typically, a larger percentage of flights in Europe depart post their ETOTS as compared to the percentage of flights that take-off in advance of their ETOTS [135], then within one standard deviation, the use of $\sigma = \mu$ value enables the analysis to have approximately 84% of aircraft in the sample delayed rather than taking-off in advance of their ETOTS.

To have representative results, the simulation is run 99 times²³ with each run resulting into a different number of conflicts removed. **Figure 79** shows the frequency distribution of the difference in the number of conflicts removed without considering the above deviations (benchmark value) and the number of conflicts removed considering the above ETOT deviations. From the results in **Figure 79**, at a 95% confidence level there is a mean value of approximately nine conflicts unresolved

²³ 99 runs is the maximum number of runs possible in NEST conflict detection tool that can be run in parallel when using the same σ and μ on the same traffic sample.

(equivalent to 18.75% of the total conflict removed in the benchmark value) when deviations are considered. These results provide an insight into the effect of uncertainties on removal of conflicts by pre-flight TOA adjustments. However, further development of this analysis is required to better assess this effect in the future. Deviations in aircraft ETOTs may result from different factors occurring at different planning and execution layers of the flight. Consequently, σ and μ values are likely to be different for different traffic samples. Therefore, a more accurate estimation of these values for any given traffic sample is necessary for a complete analysis as proposed in further works discussed in Section 8.3.

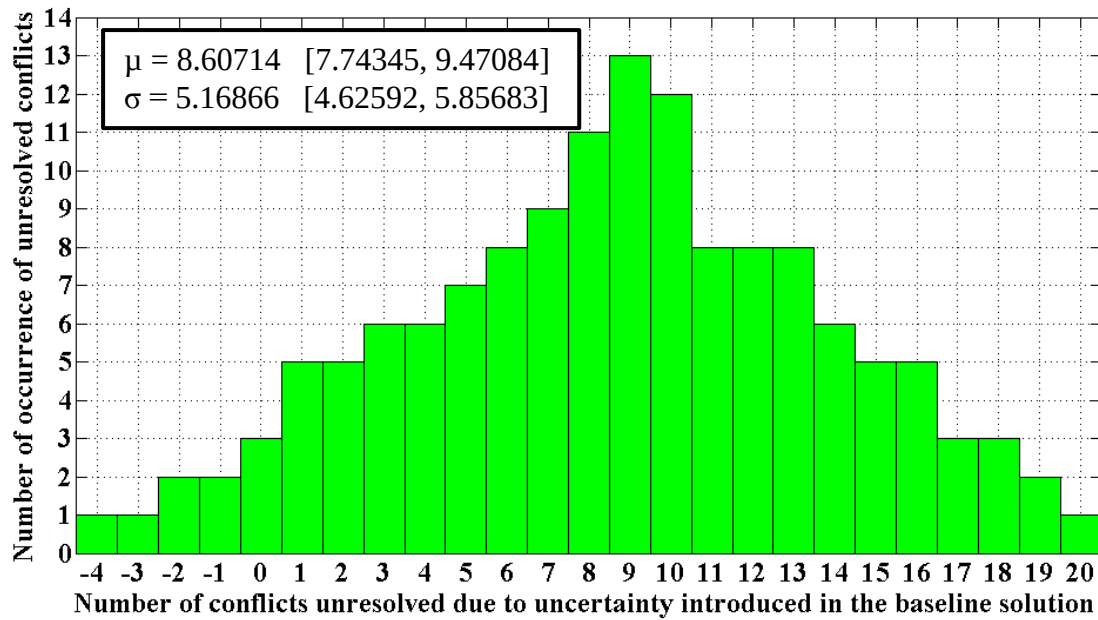


Figure 79: The difference in the number of conflicts removed with and without considering aircraft ETOT uncertainties

7.4.5 Experts Opinion on the Implications of Pre-flight De-confliction for Complementary Qualitative Analysis

The assessment provided in this chapter so far has been based on a quantitative analysis. However, a qualitative assessment usually provides sound operational judgment of the new ATM methods in terms of their operational feasibility and their potential practical implications. Qualitative analysis should then not be completely overlooked in favour of quantitative analysis. For this reason, the quantitative assessment in this thesis is

complemented by a basic qualitative assessment. The qualitative assessment is based on ATM Subject Matter Experts' (SMEs') opinion obtained from SMEs' answers of a small-scale structured questionnaire. The questionnaire was preliminary intended to elaborate on the implications of PARTAKE project²⁴ from the perspective of different ATM stakeholders. Given that PARTAKE project and the ATFCM DCB method proposed in this thesis share some similarities; some questions applicable to both were included in the questionnaire. Of particular interest in this thesis, are the answers to the questions that intended to survey the opinions of the SMEs, gathered from different ATM stakeholders with respect to the following aspects coinciding with the identified current ATM stakeholders concerns (see Section 2.5.2):

1. ***Airspace Capacity***: Opinions from the ATM stakeholders on envisaged capacity benefits as a result from the reduction of en-route conflicts.
2. ***Flight/Network efficiency***: ATM stakeholders' preferences between a robust pre-flight solution that removes only a few conflicts and a total removal of conflicts at tactical level but with poor trajectory adherence.
3. ***Safety concerns***: Benefits on safety as the result from the reduction of en-route conflicts as envisaged by the ATM stakeholders.

In total, 25 SMEs from the following ATM stakeholder groups have participated:

1. Network managers: 7 respondents;
2. Air navigation service providers: 8 respondents;
3. Airspace users: 4 respondents;
4. Airport managers: 6 respondents.

These ATM stakeholders were required to answer dichotomous questions corresponding to the above aspects. Statistics of the answers from all stakeholder groups are combined

²⁴ The PARTAKE project enhances air space user's trajectory preferences relying on robust Trajectory Based Operation (TBO) mechanism by relaxing tight interdependencies between trajectories. 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 departures time changes by Air Traffic Controllers (ATCOs) at tactical phase.

for each question to generalise and summarise their perceptions on the implication of the proposed ATFCM DCB method on each aspect, as shown in **Table 9**.

Questions	Response	Percentage
Do you envisage any capacity benefits due to the reduction in en-route conflicts?	YES	72%
	NO	28%
Is it preferable to remove few conflicts at pre-flight phase providing a robust solution rather than removing the maximum amount of conflicts at tactical level affected by poor trajectory adherence?	YES	73.3%
	NO	26.7%
Do you envisage an improvement of safety level by reducing en-route conflicts?	YES	62.5%
	NO	37.5%

Table 9: Summary of SMEs opinions on the proposed ATFCM DCB Method

As shown in **Table 9**, 72% answers from the respondents are in favour of envisaged capacity benefits due to the reduction in en-route conflicts. The preference on robust solution of pre-flight removal of only a few conflicts over tactical maximum removal of conflicts with poor trajectory adherence manifests in 73.3% of the positive responses, whereas 62.5% of the SME responses indicate an envisaged improvement of safety levels due to reduction in en-route conflicts.

A high percentage of stakeholders' positive opinion on capacity benefits due to a reduction in en-route conflicts substantiates the assertions previously stated in Section 2.5.2. These assertions are:

1. A reduction in en-route conflicts due to the proposed ATFCM DCB method could reduce the current ATCOs' workload, enabling them to accommodate traffic increase at constant workload.
2. The accommodation of traffic increase implies that ATCOs could accommodate new flights at constant workload or even accommodate those flights that are currently delayed at constant workload, making it possible to use the current available ATC resources to increase the airspace capacity.

Notwithstanding the high percentage of positive answer on the capacity benefits, the smaller percentage of opinions on the negative answer is also valuable and cannot be overlooked. The negative answers can be attributed for instance, to the fact that although the reduction of en-route conflicts implies a significant reduction of ATC workload associated to SM tasks, there has not been a clear direct link yet established between ATC separation management tasks and the increase in airspace capacity associated to it. Indeed, the maximum capacity of airspace depends on a complex interaction of several factors, some of which cannot be accurately predicted in advance. Hence, it cannot be directly extracted from the pre-flight reduction of en-route conflicts alone without considering the interaction of other factors. A comprehensive review of several factors affecting the airspace capacity is provided by Majumdar [13]. He identifies the main drivers of the airspace capacity as being the physical aspects of the sector (size and route configuration) and factors relating to the movement of air traffic through the airspace. He also identifies mediating factors affecting the airspace capacity which includes ATCO cognitive strategies to process traffic information, state of the ATCO such as age and experience and the quality and state of equipment used by the ATCO.

Table 9 also shows a higher preference on the robust solution with pre-flight removal of only a few conflicts over the total tactical removal of conflicts with poor trajectory adherence. This result also strongly substantiates the assertion made in Section 2.5.2 that one of the major invariant ATM stakeholders' concerns is the flight/network inefficiency caused by the current ATFCM DCB inefficiency and its associated ATC tactical interventions. A reduction of conflicts at pre-flight phase ensures that the current ATC tactical interventions are reduced. This reduction then implies the diminution of aircraft manoeuvres which leads to fuel consumption reduction and as the aircraft maintain their adherence to (follow more accurately) the planned trajectory, they also better reserves the flight punctuality, improving flight/network predictability.

As shown in **Table 9**, the lowest percentage of the positive answer was obtained on the envisaged improvement of safety level due to the reduction of en-route conflicts. Although this percentage (62.5%) implies a higher consensus in favour of improved

safety level, this percentage is still considered as marginal. This result may reflect a wide lack of confidence in the system performance in future. For instance, although the reduction of en-route conflicts implies that ATCOs will be more involved in traffic monitoring and supervision activities rather than conflict detection and resolution activities, there is a general concern on how emergencies and contingencies will be managed in maintaining the desired level of safety. Increasing level of automation informed by new Decision Support Tools (DSTs) is seen as a major enabler for increasing safety in the future ATM system concept. However, in a case of automation failure, confidence in system's safety will rely on the ATCO's rapid and effective response. To maintain integrity of the system, clear defined contingency measures are required to provide assurance of ATCO's rapid and effective response in the future ATM system. This is also to avoid making the human factor to be the weak element of the overall system. If these contingency measures are well defined, it will then more likely increase the ATM stakeholders' confidence in the future ATM system and the associated new separation management methods.

In summary, the opinions gathered from SMEs generally indicate a significant agreement among ATM stakeholders that hotspot identification and mitigation at pre-flight phase could improve their three main aspects of concern; increasing the airspace capacity, efficiency and safety. Although this qualitative analysis is considered as complementary rather than key to support the quantitative assessment in this thesis, it still indicates that by enabling pre-flight aircraft de-confliction, the proposed ATFCM DCB has a high potential of acceptability for implementation in the future ATM system. Discussion on the potential operational impact of the proposed ATFCM DCB method to future ATM system is provided in Section 8.2.

8 CONCLUSIONS AND FUTURE WORKS

This Chapter summarises the thesis objectives defined in Chapter 1 by discussing the thesis main achievements and its operational implications to the current as well as future Air Traffic Management (ATM) environment. It also outlines the potential limitations and provides several recommendations for future work.

8.1 Research Main Achievements

The new ATM paradigms such as defined by the Single European Sky ATM Research (SESAR) require new ATM methods that ensure adequate airspace capacity to cope with the expected increase in air traffic demand, whilst enabling increased flight efficiency and flight safety. This research is aligned to the new ATM paradigm shift from the current sector- based to trajectory-based management of the air traffic.

The current management of the air traffic is based on the physical volumes of the Air Traffic Control (ATC) sectors and their assigned capacity limit, established in terms of sector entry count. Anytime this limit is reached, the involved aircraft are regulated through ground delays or re-routing by the Air Traffic Flow and Capacity Management (ATFCM) in order to maintain an acceptable Air Traffic Controllers' (ATCOs') workload

In current operations of ATFCM Demand and Capacity Balancing (DCB) at pre-flight (strategic/pre-tactical levels), the limit on sector entry count is determined but aircraft conflicts inherent in aircraft flight plans are not considered. This leaves them to be only tactically detected and resolved by the ATCOs during the flight execution phase. The current ATFCM DCB function then assumes that the aircraft trajectories are compatible with each other as long as the entry count limit in the ATC sectors is not exceeded. The overall airspace capacity is then defined based on the capacity of individual ATC sectors contained within, which is constrained by the workload of ATCOs. The ATC workload is currently mainly associated to the required tactical interventions in Separation Management (SM) tasks, which involves detecting and resolving the conflicts for any given aircraft population. The current ATFCM DCB measures based on sector entry count are anchored to the conventional ATM concept, "the airspace-

based operations”, instead of the new “Trajectory Based Operations (TBO)” concept and it is broadly recognised that the former is no longer efficient to deal with the sustained increasing traffic density.

To achieve the SESAR ATM target concept, TBO should enable measures for pre-flight de-confliction of aircraft trajectories in order to reduce the number of conflicts solved by ATC at tactical level. For en-route operations, this expectation is stated in SESAR master plan “*the goal of the SESAR ATM target concept is to deploy tools to manage complex situations in order to reduce ATC workload by strategic de-confliction measures within the new ATM system*”. There is an existing gap between the above SESAR expectation and the existing ATFCM DCB research efforts. It has not been yet described how aircraft de-confliction at pre-flight phase will be achieved, nor have it been elaborated how it should reduce the ATC workload and improve the airspace capacity.

The research conducted in this thesis bridges the above apparent gap between the existing ATFCM DCB methods and SESAR expectation by describing a new ATFCM DCB method to achieve de-confliction of aircraft trajectories at pre-flight phase.

The proposed ATFCM DCB method changes the capacity-limiting factor measure currently established by the entry count. This is achieved by applying a new ATFCM DCB method that uses pre-flight identification of hotspots at en-route junctions as a different metric and developing a method of corrective actions to mitigate them at pre-flight phase, as described in Chapter 5. This method is fully aligned with the TBO concept. The method identifies the expected traffic demand that produces spatiotemporal interdependencies of aircraft planned trajectories at junctions that are likely to require ATCO SM tactical interventions.

The identified hotspots are mitigated by applying minor adjustments on the aircraft Times of Arrival (TOAs) at en-route conflicted junctions at pre-flight ATFCM DCB timeframe to achieve a well-defined minimum safe time interval between aircraft, as discussed in Section 5.4. Under TBO, the availability of data of expected TOAs at conflicted junctions before flight, as part of flight plan or Reference Business Trajectory

(RBT), enables the Network Manager (NM) to identify and assess the spatiotemporal interdependencies of trajectories and locate the hotspots. This will support the implementation of the proposed method.

The TOA adjustments are achieved through optimal changes (before and after the junctions) on speed profile of all conflicting aircraft, while considering all spatiotemporal interdependencies of all aircraft trajectories as well as their upstream and downstream impact on the ATM network. These adjusted TOAs should be issued by the NM as time constraint requirements in the initial RBTs. These constraints can be specified as the required Target Time to Overfly (TTO) for the en-route crossing and merging points or Target Time to Arrival (TTA) at Terminal Manoeuvring Areas (TMAs) entry points.

The main achievement of this thesis in the operational ATM context, therefore, is a comprehensive method to maintain the number and complexity of the expected required ATC SM interventions at a reasonable level from the ATCOs workload perspective that leads to increasing airspace capacity, flight efficiency and providing a positive impact on safety at a global network scope.

The computation of proposed TOAs/speed changes is based on a novel Linear Programming (LP) optimisation model where the total amount of distance-weighted speed changes is minimised and the aircraft Targeted Time of Arrival (TTA) are maintained as the constraints. The global time performance at conflicted junctions for the set of aircraft is also maintained as a constraint to keep the entropy of traffic flow network, minimising disruptions to the ATCOs' situational awareness. Maximum thresholds of the allowed speed changes are also imposed. With the LP optimisation model, the scalability problem that usually occurs in the existing ATFCM optimisation methods is minimised.

The analysis in this thesis uses realistic maximum speed change thresholds (i.e. 6% or 10%, see Sections 6.2.1 and 7.4.1) as the constraint that are assumed to be realistic and practical from both ATCO daily operations and Airspace User (AU) perspectives. The proposed ATFCM DCB method proves a number of successful de-conflicted aircraft

inbound of junctions without exceeding any of the above speed change thresholds. This finding is important in determining the performance of the proposed method when the traffic density at junctions is high such as on busy route network merging junctions. The analysis shows that the number of aircraft inbound a junction in 1-hour period that can be successfully de-conflicted does not exceed six and eight aircraft with a probability of aircraft simultaneous arrival at junction of 10^{-5} with an imposed maximum speed change thresholds of 6% and 10%, respectively.

The thesis analysis also concludes that to achieve a probability of aircraft simultaneous arrival at junction of 10^{-5} , the TOA between any two consecutive aircraft requires at least 9.4 minutes of time separation. This indicates that a maximum inbound capacity (the frequency of traffic) at any junction is limited to six aircraft per hour, as discussed in Section 5.5. The thesis also shows that when the arriving traffic demand reaches the inbound flow capacity at a junction, the required speed/TOA changes increases monotonically for some aircraft (See Section 6.2). To avoid this behaviour, the subsequent analysis in the thesis establishes proposed specific traffic demand and operational conditions to modulate the speed/TOA changes. This modulation has been proved to enable a certain degree of fairness among all involved aircraft.

The thesis also includes a basic assessment on the effects of speed/TOA changes on the flight operating costs for different traffic demands at a junction. Aircraft performance data for an A320 aircraft extracted from EUROCONTROL Base of Aircraft Data (BADA) performance model is used to compute the fuel consumptions for given required speed changes. The analysis shows an average change of 3.5% in fuel consumption for a typical A320 aircraft to achieve a conflict free scenario of six-aircraft inbound a junction in an hour (corresponding to a probability of aircraft simultaneous arrival at junction of 10^{-5}) when these aircraft are all initially in conflict.

The thesis uses a sample of real planned flights for the most peak 30-minute time window on 9 September 2016 (the busiest day of the year) containing 1169 planned trajectories in the whole ECAC area to compute the speed/TOA changes on a realistic traffic network. The planned trajectories are extracted from EUROCONTROL Demand Data Repository2 (DDR2) database and analysed using EUROCONTROL Network

Strategic Tool (NEST). The proposed DCB method is applied on the traffic sample for different conflict scenarios as well as on a forecasted scenario of traffic in ECAC area for 2022 (generated using EUROCONTROL Statistics and Forecasts (STATFOR) data and NEST forecasting tool), as discussed in Chapter 7. The results show a good performance in terms of the computed aircraft speed/TOA adjustments feasibility from both AUs and ATCO's perspectives with 83.3% of the computed aircraft speed change range within $\pm 6\%$ of the nominal aircraft speed, 19.8% within $\pm 3\%$ of nominal aircraft speed and all speed changes within 10% of nominal aircraft speed. The simulations also show that the proposed method is able to remove completely the nominal conflicts with minimum cascading effects on initially non-conflicted traffic for both current and future traffic scenarios.

Following the results from the simulation and as part of verification process to complement the quantitative analysis, the thesis also presents Subject Matter Experts (SMEs) opinions based on which a qualitative analysis is performed on the performance of proposed approach in reducing the current ATCO SM tactical interventions, hence reducing their workload and improving the airspace capacity. The opinions are collected from different ATM stakeholder groups as respondents of a small-scale structured questionnaire (see Section 7.4.5). The analysis of these opinions shows a high acceptability potential of the proposed ATFCM DCB method for implementation in the future ATM system.

The results obtained in this thesis indicate that the proposed ATFCM DCB method could reduce the current ATCOs' SM tactical interventions, hence, reducing their workload and improving the airspace capacity. Therefore, the performance of the proposed method should have significant ATM operational implications in light of its possible impact on flight/network efficiency, airspace capacity and flight safety as discussed in Section 8.2 below.

8.2 Potential Operational Impact to ATM System

To assess the implication of the proposed ATFCM DCB method on the ATM network efficiency, this thesis takes a global scope scenario by examining the ECAC airspace in

its totality independent of sector boundaries. This scenario is defined in line with the ICAO airspace operational target requirements to remove the network inefficiencies due to the current sector fragmentations of European airspace (See Section 4.2).

Since the proposed ATFCM DCB solution considers the entire aircraft trajectories and the cascading effects of the solution that are not considered in the local solutions of the current ATFCM sector-based decisions, it also suggests feasible and efficient solutions in the global network perspective. The consideration of all entire aircraft trajectories defined as RBTs and their interdependencies at pre-flight phase, allows the proposed ATCM DCB method to compute feasible de-conflicted scenarios for the whole network that preserves trajectories preferred by the AUs. Indeed, the solution on these global network scenarios suggests a reduction of ATC separation interventions, implying diminution of conflict avoidance manoeuvres from the involved aircraft. This could then lead to a reduction in fuel consumption, maintaining flight punctuality and improving the predictability since the flights will follow their planned trajectories with fewer trajectory modifications. Moreover, unlike the current sector based management of air traffic that confines aircraft trajectories in fixed conventional routes, the proposed ATFCM DCB method supports the implementation of Free-Routing (FR) concept enabling routes that are more direct which is expected to save flight-operating costs due to its associated reduction in aircraft fuel consumption and flight time. Providing de-confliction of trajectories before departure (pre-flight SM) in free-route airspace should support the implementation of FR and flight-operating costs savings.

The added value of the proposed ATFCM DCB method on the airspace capacity is introduced by its ability to perform the pre-flight trajectory de-confliction of a large number of trajectories. This enables the NM to deliver de-randomised and conflict-free traffic scenarios to the ATC tactical level, hence reducing the probability of ATCO SM interventions (minimising the tactical separation maneuvers currently issued by each ATCO). Consequently, it enables them to accommodate a traffic increase without expecting an increasing workload, hence allowing the use of current available ATC resources to increase the airspace capacity.

The thesis also indicates the proposed ATFCM DCB method's contribution in the improvement of safety performance of ATM system. Since the proposed method is compatible with the other ATM safety layers, the anticipation of aircraft separation management at pre-flight phase should enable to improve the current ATM safety level. The other ATM safety layers are currently only provided by the Airspace Management (ASM) through structuring the route network in such a way that it reduces the risk of conflicts in routes, and by tactical surveillance and management of conflicts performed by the ATCOs and on-board collision avoidance systems as the final safety layers. By including another separation management function at the ATFCM DCB level acting as an additional safety layer, the expected probability of conflicts is reduced, enabling a reduction in the possibility of mid-air collisions at network level.

8.3 Limitations and Recommendations for Further work

The work conducted in this thesis has emphasized several opportunities for further research.

8.3.1 Human In-the-Loop Exercise

This thesis has opened the possibility to increase the airspace capacity from the benefit of decrease in ATCO workload associated to their tactical SM interventions, enabled by pre-flight de-confliction of aircraft trajectories. This ATC workload reduction should allow the ATC to accommodate the expected traffic increase at constant workload, making it possible to use the current available ATC resources to increment the airspace capacity. However, this anticipated increase in airspace capacity has not been sufficiently evaluated in this thesis. Further work is needed to compare the current capacity of the ECAC airspace to its capacity in a TBO environment with the implementation of the proposed pre-flight de-confliction method. This can be properly achieved through human in the loop exercises. Moreover, to achieve a complete evaluation on the possible increment in the airspace capacity due to pre-flight de-confliction, the effect of other factors that affects the overall ATCOs' performance and workload should also be assessed.

8.3.2 Estimation of Take-off Time Deviations

A simple analysis on the effect of uncertainties on the solution of the proposed ATFCM DCB method has been performed. This analysis established the decrease in number of conflicts solved when the current level of deviations in aircraft Estimated Take off Times (ETOTs) is considered. The use of ETOT deviations in this analysis is because in the current ATM operations, it is universally accepted that ground delays are cheaper and safer than airborne delays. Consequently, any foreseen delay in the system is anticipated prior to take-off at departure airport, making deviations in the ETOTs the most significant deviation affecting pre-flight DCB. These deviations however, are difficult to estimate as they originate from different factors occurring at different parts of the ATM network. Although 4.4 minutes obtained from EUROCONTROL Performance Review Report (PRR) was used in this thesis as the mean ETOT deviation, a rough assumption on the standard deviation from this mean value was made. Simulations that compare actual flown trajectories in ECAC airspace to the planned trajectories in order to better estimate the actual levels of ETOT deviations should be considered for further research.

8.3.3 Pre-flight De-confliction Optimisation with Cost Index Variation

The formulated optimisation problem in this thesis minimises the distance weighted speed changes. However, there is no statement about airline's perspectives in the formulation. Flight Operational Centres (FOCs) use different Cost Index (CI) values to schedule their flights. A CI represents an airline's business intentions on a flight. Since business intentions are proprietary and vary from one Airspace User (AU) to another, the CI preferred by AUs also varies. Considering the variations in CI preferences among AUs, care has been taken in this thesis to ensure that CI is unaffected in the problem formulation by ensuring that aircraft flight time is maintained. Indeed, obtaining CI information is challenging since AUs consider it as sensitive business information and they are reluctant to share it due to their competitive market environment. Furthermore, AUs' CI preferences tend to change overtime as the air traffic and economic situations change. For instance, when fuel prices increase, airlines tend to reduce their CI to reduce more on fuel consumption. Although it was not seen possible to use CI to

represent AUs' preferences in the formulated optimisation problem, it is understood that some of the computed speed changes required to remove conflicts may collide with airlines preferences. Thus, further research is required in this perspective. To be able to consider CI in the optimisation of TOA/speed changes given its variation across airlines and in different operational situations, further work should consider CI variation constraints in the formulation of pre-flight de-confliction optimisation problem. The CI values should be confidentially acquired from different types of airlines operating with different economic policies. This will enable to assess the effect of the pre-flight TOA adjustments by airline type and in relevant economic situations.

8.3.4 Exploration of Complementarity with PARTAKE

This thesis postulated that in cases where the speed changes computed by the proposed model maybe high especially when computed to achieve very low probabilities of aircraft simultaneous arrival at junction, they are likely not to be accepted by the AUs. Under these cases, the thesis suggests that other ATFCM measures could be applied together with the proposed ATFCM DCB method to reduce the required speed changes to lower values. One identified measure that could be applied to complement the proposed method is the cooPerative depArtuRes for a compeTitive ATM networkService (PARTAKE). PARTAKE is a new STAM measure studied by SESAR. It focusses on improving the air traffic dynamic demand capacity balancing by identifying conflicts at network level and re-adjusting the ETOTs of the affected aircraft within their assigned nominal Calculated Take-Off Time (CTOT) to remove the identified conflicts. The possible complementarity between the ATFCM DCB method proposed in this thesis and PARTAKE should be explored. Further research should explore how to combine the two approaches into a new STAM measure. With this new STAM measure, if the computed TOA adjustments at junctions to remove conflicts require speed changes that maybe unrealisable for some aircraft, ETOTs of the involved aircraft can be adjusted. This should enable to relax TOA separation intervals at junctions of the involved aircraft at junction, reducing the required TOA/speed changes to lower values.

REFERENCES

1. European Commission. Annual Analyses of the EU Air Transport Market 2012. 2013. Available at:
https://ec.europa.eu/transport/sites/transport/files/2016_eu_air_transport_industry_analyses_report.pdf (Accessed: 15 May 2016)
2. Sáez Nieto FJ. The long journey toward a higher level of automation in ATM as safety critical, sociotechnical and multi-Agent system. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2016; 230(9): 1533–1547. Available at: DOI:10.1177/0954410015596763
3. Perovic J. The Economic Benefits of Aviation and Performance in the Travel & Tourism Competitiveness Index. IATA. 2013. Available at:
http://www3.weforum.org/docs/TTCR/2013/TTCR_Chapter1.4_2013.pdf (Accessed: 10 June 2017)
4. ATAG. Aviation benefits beyond borders. Air Transport Action Group. 2014. Available at:
https://aviationbenefits.org/media/149668/abbb2016_full_a4_web.pdf (Accessed: 18 September 2018)
5. Industry High Level Group (IHLG). Aviation Benefits 2017. Airports Council International. 2017. Available at: <https://store.aci.aero/product/aviation-benefits-2017-industry-high-level-group-report/> (Accessed: 18 September 2018)
6. Geels IFW. The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860-1930). Technology Analysis and Strategic Management. 2005; 17(4): 445–476. Available at: DOI:10.1080/09537320500357319
7. Markard J., Truffer B. Innovation processes in large technical systems: Market liberalization as a driver for radical change? Research Policy. 2006; 35(5): 609–625. Available at: DOI:10.1016/j.respol.2006.02.008
8. La Porte T. The United States Air Traffic System: Increasing Reliability in the Midst of Rapid Growth. 1988. Available at:
<https://escholarship.org/content/qt2xh2r82r/qt2xh2r82r.pdf> (Accessed: 19 September 2018)

9. ICAO. Doc 9854 - Global Air Traffic Management Operational Concept. 1st edn. International Civil Aviation Organization. Quebec, Canada: International Civil Aviation Organization; 2005.
10. Silva S Da. Global ATM Operational Concept. ICAO. 2010. Available at: https://www.icao.int/ESAF/Documents/meetings/2010/wdnpf_ans/docs/wp_04.pdf (Accessed: 18 September 2018)
11. SESAR Consortium. SESAR Definition Phase - Deliverable 2: Air Transport Framework - The Performance Target. 2006. Available at: https://www.eurocontrol.int/eec/public/standard_page/EEC_News_2007_2_SESAR.html (Accessed: 18 September 2018)
12. Zhang W., Kamgarpour M., Sun D., Tomlin CJ. A hierarchical flight planning framework for air traffic management. *Proceedings of the IEEE*. 2012; 100(1): 179–194. Available at: DOI:10.1109/JPROC.2011.2161243
13. Majumdar A., Ochieng W. Factors Affecting Air Traffic Controller Workload: Multivariate Analysis Based on Simulation Modeling of Controller Workload. *Transportation Research Record: Journal of the Transportation Research Board*. 2002; 1788: 58–69. Available at: DOI:10.3141/1788-08
14. Majumdar A., Ochieng WY. The factors affecting airspace capacity in Europe : A Framework Methodology based on Cross Sectional Time-Series Analysis using Simulated Controller Workload Data. *ATM R&D Seminar*. Berlin, Germany, 14 - 17 June, Berlin; 2011.
15. EUROCONTROL. An assessment of Air Traffic Management in Europe during the calendar year 2016 - Draft Final Report For consultation with stakeholders. 2017. Available at: <https://www.eurocontrol.int/sites/default/files/publication/Draft-performance-review-report-prr-2016.pdf> (Accessed: 18 September 2018)
16. FAA. NextGen implementation plan. 2016. Available at: https://www.faa.gov/nextgen/media/NextGen_Implementation_Plan-2016.pdf (Accessed: 18 September 2018)
17. SESAR Joint Undertaking. Modernising the European Sky. 2014. Available at: <https://www.sesarju.eu/sites/default/files/brochure-2014-modernising-european->

- sky-final.pdf (Accessed: 14 June 2018)
18. CARATS. Long-term Vision for the Future Air Traffic Systems :Changes to Intelligent Air Traffic Systems. 2010. pp. 1–56. Available at: <http://www.mlit.go.jp/common/000128185.pdf> (Accessed: 19 September 2018)
 19. Eurocontrol. Challenges of Growth 2013. EUROCONTROL. 2013. Available at: <https://www.eurocontrol.int/sites/default/files/article/content/documents/official-documents/reports/201306-challenges-of-growth-2013-task-4.pdf> (Accessed: 18 February 2018)
 20. Burghouwt G., Boonekamp T., Suau-Sanchez P., Volta N., Pagliari R., Mason K. The impact of airport capacity constraints on air fares. 2017. Available at: http://www.seo.nl/uploads/media/2017-04_The_impact_of_airport_capacity_constraints_on_air_fares.pdf (Accessed: 14 August 2018)
 21. Mondoloni S., Swierstra S. Commonality in disparate trajectory predictors for air traffic management applications. AIAA/IEEE Digital Avionics Systems Conference. Washington D.C, USA, 1-03 November 2004, Hyatt Regency Crystal City, Washington D.C; 2005. pp. 1–10. Available at: DOI:10.1109/DASC.2005.1563348
 22. EUROCONTROL. Capacity assessment and planning guidance document. 2013. Available at: <http://www.eurocontrol.int/sites/default/files/content/documents/nm/airspace/capacity-assessment-planning-guidance-doc-v2-8final.pdf> (Accessed: 10 June 2015)
 23. Strybel TZ., Vu KPL., Chiappe DL., Morgan CA., Morales G., Battiste V. Effects of NextGen Concepts of Operation for Separation Assurance and Interval Management on Air Traffic Controller Situation Awareness, Workload and Performance. International Journal of Aviation Psychology. 2016; 26(1–2): 1–14. Available at: DOI:10.1080/10508414.2016.1235363
 24. SESAR. European ATM Master Plan 2015. 2015. Available at: <https://ec.europa.eu/transport/sites/transport/files/modes/air/sesar/doc/eu-atm-master-plan-2015.pdf> (Accessed: 15 February 2016)
 25. ICAO. Doc 9613, Performance Based Navigation (PBN) Manual. 3rd edn.

- Quebec, Canada: International Civil Aviation Organization, Vol.9; 1955. 544 p.
Available at: DOI:10.1017/S0020818300030885
26. Flin RH., Martin L. Behavioral Markers for Crew Resource Management: A Review of Current Practice. *International Journal of Aviation Psychology*. 2001; 11(1): 95–118. Available at: DOI:10.1207/S15327108IJAP1101
 27. Kirk DB., Heagy WS., Yablonski MJ. Problem Resolution Support for Free Flight Operations. *IEEE Transactions on Intelligent Transportation Systems*. 2001; 2(2): 72–79. Available at: DOI:10.1109/6979.928718
 28. Gurtner G., Bongiorno C., Ducci M., Micciché S. An empirically grounded agent based simulator for the air traffic management in the SESAR scenario. *Journal of Air Transport Management*. 2017; 59: 26–43. Available at: DOI:10.1016/j.jairtraman.2016.11.004
 29. Brochard M. En Route Air Traffic Soft Management Ultimate System. 2005. Available at:
https://www.eurocontrol.int/eec/gallery/content/public/documents/EEC_INO_documents/INO_workshop_2005/Papers/15_M_Brochard_ERASMUS.pdf
(Accessed: 4 July 2017)
 30. Geser A., Munoz C. A geometric approach to strategic conflict detection and resolution. *The 21st Digital Avionics Systems Conference, 2002. Proceedings.* CA, USA, 27-31 October 2002, Irvine, CA: IEEE; 2002. pp. 1–11. Available at: DOI:10.1109/DASC.2002.1067985
 31. Philippe DA. Could Erasmus Speed Adjustments Be Identifiable By Air Traffic Controllers? *The 7th USA/ Europe Air Traffic Management Research and Development Seminar.* Barcelona, Spain 02 - 05 July 2007, Barcelona: EUROCONTROL; 2007. pp. 1–11. Available at:
http://www.atmseminar.org/seminarContent/seminar7/papers/p_164_IAC.pdf
 32. Paielli RA. Trajectory Specification for High-Capacity Air Traffic Control. *Journal of aerospace computing, information and communication*. 2005; 2(9): 361–386. Available at: DOI:10.2514/1.12335
 33. SESAR Joint Undertaking. Step 1 Business trajectory final OSED. 2016. Available at:

- https://www.sesarju.eu/sites/default/files/solutions/03_OSED_Solution_37_07_06_02_-D56-Step_1_Final_OSED_2016_Edition_5.1.pdf (Accessed: 10 February 2018)
34. SESAR Joint Undertaking. SESAR 2020 Concept Of Operations. 2017.
Available at:
<https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5b6d2b912&appId=PPGMS> (Accessed: 18 September 2018)
 35. Nieto FJS. The long journey toward a higher level of automation in ATM as safety critical, sociotechnical and multi-Agent system. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2015; 0(0): 0954410015596763. Available at: DOI:10.1177/0954410015596763
 36. ICAO. Annex 11 to the Convention on International Civil Aviation - Air Traffic Services. 13th edn. Quebec, Canada: International Civil Aviation Organization; 2001.
 37. CANSO. Global Air Navigation Services Performance Report 2017. 2014.
Available at: [https://www.canso.org/system/files/Global Air Navigation Service Performance Report 2017 ANSP View.pdf](https://www.canso.org/system/files/Global%20Air%20Navigation%20Service%20Performance%20Report%202017%20ANSP%20View.pdf) (Accessed: 18 April 2017)
 38. ICAO. ICAO Doc 4444: Procedures for Air navigation Services. 16th edn. Quebec, Canada: International Civil Aviation Organization; 2016. Available at: <http://flightservicebureau.org/wp-content/uploads/2017/03/ICAO-Doc4444-Pans-Atm-16thEdition-2016-OPSGROUP.pdf>
 39. Rodionova O., Sbihi M., Delahaye D., Mongeau M. Optimization of aircraft trajectories in North Atlantic oceanic airspace. The 5th International Conference on Research in Air Transportation. California, USA, 22-25 May 2012, Berkeley, California: ICRAT; 2012.
 40. ICAO. Doc 9689-AN/953 - Manual on airspace planning methodology for the determination of separation minima. 1st edn. Quebec, Canada: International Civil Aviation Organization; 1998. Available at: DOI:10.1007/s13398-014-0173-7.2
 41. Gianazza D. Airspace configuration using air traffic complexity metrics. The 7th USA/Europe Air Traffic Management Research and Development Seminar. Barcelona, Spain, 02-05 July 2007, Barcelona: EUROCONTROL; 2007.

42. Bichot C-E., Durand N. A tool to design Functional Airspace Blocks. The 7th USA/ Europe Air Traffic Management Research and Development Seminar. Barcelona, Spain 02 - 05 July 2007, Barcelona: EUROCONTROL; 2007.
43. Gianazza D., Alliot J-M., Granger G. Optimal Combinations of Air Traffic Control Sectors using Classical and Stochastic Methods. Proceedings of the International Conference on Artificial Intelligence. Vol.2, Nevada, USA, 24-27 June 2002, Las Vegas, Nevada, USA: IJCAI; 2002. pp. 649–655.
44. Tang J., Alam S., Lokan C., Abbass HA. A multi-objective approach for Dynamic Airspace Sectorization using agent based and geometric models. *Transportation Research Part C: Emerging Technologies*. 2012; 21(1): 89–121. Available at: DOI:10.1016/j.trc.2011.08.008
45. Bloem M., Gupta P. Configuring Airspace Sectors with Approximate Dynamic Programming. 27th International Congress of the Aeronautical Sciences. Nice, France, 19-24 September 2010, Nice; 2010. pp. 1–13. Available at: http://www.aviationsystemsdivision.arc.nasa.gov/publications/2010/bloem_ICAS_2010_conf_sectors_ADp.pdf
46. Wallace MO (Maurice O. Maastricht Upper Area Control Centre. As the crow flies, Free Route Airspace Maastricht. 2007. Available at: DOI:10.1353/cal.2007.0189 (Accessed: 18 September 2018)
47. Majumdar A., Ochieng W. Factors Affecting Air Traffic Controller Workload: Multivariate Analysis Based on Simulation Modeling of Controller Workload. *Transportation Research Record: Journal of the Transportation Research Board*. January 2002; 1788: 58–69. Available at: DOI:10.3141/1788-08
48. Dupuy M. Framework for the Analysis of Separation Related Incidents in Aviation. PhD. Imperial College London; 2012.
49. Tobaruela G., Schuster W., Majumdar A., Ochieng WY., Martinez L., Hendrickx P. A method to estimate air traffic controller mental workload based on traffic clearances. *Journal of Air Transport Management*. 2014; 39: 59–71. Available at: DOI:10.1016/j.jairtraman.2014.04.002
50. EUROCONTROL. Guidelines for NSAs for the Development of the ANSP Designation Process. 2011. Available at:

- https://www.eurocontrol.int/sites/default/files/article/files/DSS_CAA-NSA_GUI_ANSP_OVS_process_01_V3.0_June_2013.pdf (Accessed: 12 May 2018)
51. Kuchar JK., Yang LC. A Review of Conflict Detection and Resolution Modeling Methods. *IEEE Transactions on Intelligent Transportation Systems*. 2000; 1(4): 179–189. Available at: DOI:10.1109/6979.898217
 52. Delahaye D., Alliot JM., Schoenauer M., Farges JL. Genetic algorithms for automatic regroupement of air traffic control sectors. *Proceedings of the conference on Evolutionary Programming*. San Diego, USA, 25 September 1994, 1995, Calif, San Diego: MIT Press; 1994. p. 8.
 53. ICAO. Doc 9854 Global Air Traffic Management Operational Concept. 1st edn. International Civil Aviation Organization. Quebec, Canada: International Civil Aviation Organization; 2005. Available at: [https://www.icao.int/Meetings/anconf12/DocumentArchive/9854_cons_en\[1\].pdf](https://www.icao.int/Meetings/anconf12/DocumentArchive/9854_cons_en[1].pdf) (Accessed: 18 August 2017)
 54. EUROCONTROL. ATFCM Operations Manual. 21st edn. Brussels: EUROCONTROL; 2017.
 55. EUROCONTROL. ATFCM User Manual. 22nd edn. Brussels: EUROCONTROL; 2016.
 56. European Civil Aviation Conference. About ECAC. 2018. Available at: <https://www.ecac-ceac.org/> (Accessed: 12 January 2018)
 57. Ball M., Barnhart C., Dresner M., Neels K., Odoni A., Peterson E., et al. Total Delay Impact Study: A Comprehensive Assessment of the Costs and Impact of Flight Delay in the United States. 2010. Available at: https://isr.umd.edu/NEXTOR/pubs/TDI_Report_Final_10_18_10_V3.pdf (Accessed: 18 March 2017)
 58. Gwiggner C., Kageyama K., Nagaoka S. Propagation of Airspace Congestion. An Exploratory Correlation Analysis. 3rd International Conference on Research in Air Transportation. Varginia, USA, 1-4 June 2008, George Mason University, Fairfax: ICRAT; 2008. pp. 69–75.
 59. ICAO. Doc 9971-Manual on Collaborative Air Traffic Flow Management. 1st

- edn. Quebec, Canada: International Civil Aviation Organization; 2012.
60. Carlier S., Lépinay I de., Husatche J-C., Jelinek F. Environmental impact of air traffic flow management delays. 7th USA/Europe Air Traffic Management Research and Development Seminar. Barcelona, Spain 02 - 05 July 2007, Barcelona: EUROCONTROL; 2007. pp. 1–13.
 61. Knorr D., Chen X., Rose M., Gulding J., Enaud P. Estimating ATM Efficiency Pools in the Descent Phase of Flight. 9th USA/Europe Air Traffic Management Research and Development Seminar (ATM2011). Berlin, Germany, 14-17 June 2011, Berlin: EUROCONTROL; 2011. pp. 1–9.
 62. Adacher L., Flamini M., Romano E. Rerouting algorithms solving the air traffic congestion. AIP Conference Proceedings. Rome, Italy, 27–29 January 2017, Rome: American Institute of Physics; 2017. Available at: DOI:10.1063/1.4981993
 63. Barfield F. Autonomous collision avoidance: The technical requirements. Proceedings of the IEEE National Aerospace and Electronics Conference. Ohio, USA, 12-12 October 2000, Dayton, OH: IEEE; 2000. pp. 808–813. Available at: DOI:10.1109/NAECON.2000.894998
 64. Kuchar JK., Drumm AC. The traffic alert and collision avoidance system. Lincoln Laboratory Journal. 2007; 16(2): 277–296.
 65. Prandini M., Hu J., Lygeros J., Sastry S. A Probabilistic Approach to Aircraft Conflict Detection. IEEE Transactions on Intelligent Transportation Systems. 2000; 1(4): 199–219. Available at: DOI:10.1109/6979.898224
 66. EUROCONTROL. Strategic Guidance in Support of the Execution of the European ATM Master Plan Strategic Guidance in Support of the Execution of the European ATM Master Plan. 2009. Available at: <https://www.eurocontrol.int/sites/default/files/publication/files/surveillance-strategic-guidance-support-of-the-execution-european-atm-master-plan-20090513.pdf> (Accessed: 15 July 2017)
 67. SESAR Joint Undertaking. STEP1 V3 Final Complexity Management OSED. 2015. Available at: https://www.sesarju.eu/sites/default/files/solutions/04_OSED_Solution_17_P04_

- 07_01_D68_STEP1_V3_Final_Complexity_Management_OSED.pdf (Accessed: 18 April 2018)
68. ICAO. Annex 2 to the Convention on International Civil Aviation - Rules of the Air. 10th edn. Quebec, Canada: International Civil Aviation Organization; 2005. 1-74 p.
 69. CANSO. Transforming global ATM performance. 2018. Available at: <https://www.canso.org/> (Accessed: 15 May 2018)
 70. IATA. International Air Transport Association. 2018. Available at: <https://www.iata.org/Pages/default.aspx> (Accessed: 12 April 2018)
 71. IATA. Economic performance of the airline industry. 2014. Available at: <https://www.iata.org/whatwedo/documents/economics/iata-economic-performance-of-the-industry-end-year-2014-report.pdf> (Accessed: 12 April 2018)
 72. EUROCONTROL. European route network improvement plan. 2012. Available at: <https://www.eurocontrol.int/sites/default/files/publication/files/ernip-part-1-airspace-design-methodology.pdf> (Accessed: 18 August 2018)
 73. Boag C., Neal A., Loft S., Halford GS. An analysis of relational complexity in an air traffic control conflict detection task. *Ergonomics*. 2006; 49(14): 1508–1526. Available at: DOI:10.1080/00140130600779744
 74. Roberson B. Fuel Conservation Strategies: cost index explained Used. 2007. Available at: https://www.boeing.com/commercial/aeromagazine/articles/qtr_02_10/pdfs/AERO_FuelConsSeries.pdf (Accessed: 12 July 2018)
 75. Dareing SW., Hoitomt D. Traffic management and airline operations. *Proceedings of the American Control Conference*. AK, USA, 8-10 May 2002, Anchorage, AK: Vol.2, IEEE; 2002. pp. 1302–1307.
 76. Gao C., Johnson E., Smith B. Integrated Airline Fleet and Crew Robust Planning. *Transportation Science*. 2009; 43(1): 2–16. Available at: DOI:10.1287/trsc.1080.0257
 77. Ahmadbeygi S., Cohn A., Lapp M. Decreasing airline delay propagation by re-allocating scheduled slack. *IIE Transactions*. 2010; 42(7): 478–489. Available at: DOI:10.1080/07408170903468605

78. Schaefer AJ., Johnson EL., Kleywegt AJ., Nemhauser GL. Airline Crew Scheduling Under Uncertainty. *Transportation Science*. 2005; 39(3): 340–348. Available at: DOI:10.1287/trsc.1040.0091
79. Airbus. Getting to grips with the cost index. 1998. Available at: <http://ansperformance.eu/references/library/airbus-cost-index.pdf> (Accessed: 12 December 2017)
80. EUROCONTROL. Specification for the Initial Flight Plan. 2017. Available at: <https://www.eurocontrol.int/sites/default/files/publication/files/20130614-ifpl-spec-v1.1.pdf> (Accessed: 11 July 2018)
81. EUROCONTROL. IFPS Users Manual. 22nd edn. Brussels: European Commission; 2014.
82. Sillard, L.; Vergne, F.; Desart B. Innovative Slot Allocation. 2000. Available at: DOI:10.1177/1090820X10391211 (Accessed: 10 February 2018)
83. Bijarbooneh FH., Flener P., Pearson J. Dynamic Demand-Capacity Balancing for Air Traffic Management Using Constraint-Based Local Search: First Results. *Electronic Proceedings in Theoretical Computer Science*. 2009; 5: 27–40. Available at: DOI:10.4204/EPTCS.5.3
84. EUROCONTROL. ATFCM Operating Procedures for Flow Management Position. Brussels; 2013. Available at: <https://www.eurocontrol.int/sites/default/files/content/documents/nm/network-operations/HANDBOOK/atfcm-ops-procedures-fmp-next.pdf> (Accessed: 6 April 2018)
85. Sherali HD., Hill JM. Configuration of airspace sectors for balancing air traffic controller workload. *Annals of Operations Research*. 2013; 203(1): 3–31. Available at: DOI:10.1007/s10479-011-0837-z
86. Dubot T., Bedouet J., Degremont S. Modelling , Generating and Evaluating Sector Configuration Plans - Methodology Report of the Sesar Vp-755 Exercise. 30th Congress of the International Council of the Aeronautical Sciences. Daejeon, South korea, 25-30 September 2016, Daejeon: ICAS; 2016. pp. 1–10.
87. Gianazza D., Allignol C., Saporito N. An efficient airspace configuration forecast. *Proc of USA/Europe Air Traffic Management Research and*

- Development Seminar. California, USA, 2 July 2009, Napa, California: ATM Seminar; 2009. pp. 1–6.
88. Kopardekar P., Bilimoria K., Sridhar B. Initial Concepts for Dynamic Airspace Configuration. 7th AIAA Aviation Technology, Integration and Operations Conference (ATIO). Belfast, Northern Ireland, 18 - 20 September 2007, Belfast: AIAA; 2007. pp. 1–11. Available at: DOI:10.2514/6.2007-7763
 89. Zelinski S., Lai CF. Comparing methods for dynamic airspace configuration. 30th Digital Avionics Systems Conference - Proceedings. Washington, USA. 16-20 October 2011, Seattle, Washington: IEEE; 2011. pp. 1–12. Available at: DOI:10.1109/DASC.2011.6096043
 90. Kopardekar P., Rhodes J., Schwartz A., Magyarits S., Willems BF. Relationship of Maximum Manageable Air Traffic Control Complexity and Sector Capacity. 26th International Congress of the Aeronautical Sciences. Alaska, USA, 14 - 19 September 2008, Anchorage, Alaska: ICAS; 2008. pp. 1–12.
 91. Boucquey J., Hatel A., Irvine R., Steurs S., Huens E., Jungers M. Probabilistic Traffic Models for Occupancy Counting. SESAR Innovation Days. Belgrade, Serbia, 28 – 30 November 2017, Belgrade: SESAR; 2017. pp. 1–8.
 92. EUROCONTROL. Single European Sky. 2018. Available at: <http://www.eurocontrol.int/dossiers/single-european-sky> (Accessed: 14 January 2018)
 93. Civil Aviation Bureau of Japan. Contents Theme Topic for EIWACS 2010 CARATS : Collaborative Actions for Renovation of Air Traffic Systems. The 2nd ENRI International Workshop of ATM/CNS. Tokyo, Japan, 11-12 November 2010, Tokyo: EIWAC; 2010. pp. 7–20.
 94. ICAO ATM Requirements and Performance Panel. Trajectory Based Operations Concept. 2015. pp. 1–50. Available at: https://www.sesarju.eu/sites/default/files/documents/reports/Appendix_A_to_WP652_TBOCD_3.0.pdf (Accessed: 12 September 2017)
 95. SESAR Joint Undertaking. SWIM Concept of Operations. 2013. Available at: https://www.eurocontrol.int/sites/default/files/publication/files/del08.01.01-d41-swim_conops.pdf (Accessed: 11 February 2016)

96. Skyway. Communications, Navigation and Surveillance :At the heart of the future ATm system. 2010. Available at:
<https://www.google.co.uk/search?q=Communications%2C+Navigation+and+Surveillance+At+the+heart+of+the+future+ATm+system&oq=Communications%2C+Navigation+and+Surveillance+At+the+heart+of+the+future+ATm+system&aqs=chrome..69i57.1038j0j4&sourceid=chrome&ie=UTF-> (Accessed: 14 April 2018)
97. EUROCONTROL. System Wide Information Management (SWIM). 2017. Available at:
https://www.eurocontrol.int/sites/default/files/publication/files/201704-swim-civil-leaflet_0.pdf (Accessed: 9 July 2018)
98. EUROCONTROL. Free Route Airspace developments: for a route-free European network. Brochure FRA. 2016. Available at:
<http://www.eurocontrol.int/sites/default/files/publication/files/free-route-airspace-brochure-20161216.pdf> (Accessed: 20 May 2017)
99. International Civil Aviation Organisation. Time adherence in TBO. 2014. Available at:
http://www.sesarju.eu/sites/default/files/documents/reports/WP636_Trajectory_adherence_in_TBO.pdf?issuysl=ignore (Accessed: 28 February 2018)
100. Sankararaman S., Roychoudhury I., Goebel K. Preliminary Investigation of Impact of Technological Impairment on Trajectory-Based Operations. 17th AIAA Aviation Technology, Integration, and Operations Conference. Colorado, USA, 5-9 June 2017, Denver, CO: AIAA; 2018. pp. 1–14. Available at: DOI:10.2514/6.2017-4488
101. ICAO. 2016–2030 Global Air Navigation Plan. International Civil Aviation Organization. 2016. Available at:
<https://www.icao.int/airnavigation/Documents/GANP-2016-interactive.pdf> (Accessed: 11 September 2017)
102. Richetta O., Odoni AR. Dynamic solution to the ground-holding problem in air traffic control. Transportation Research Part A. 1994; 28(3): 167–185. Available at: DOI:10.1016/0965-8564(94)90015-9

103. Andreatta G., Romanin-Jacur G. Aircraft Flow Management under Congestion. *Transportation Science*. 1987; 21(4): 249–253. Available at:
DOI:10.1287/trsc.21.4.249
104. Vranas PB., Bertsimas DJ., Odoni AR. The Multi-Airport Ground-Holding Problem in Air Traffic Control. *Operations Research*. 1994; 42(2): 249–261. Available at: DOI:10.1287/opre.42.2.249
105. Bertsimas D., Patterson SS. The Air Traffic Flow Management Problem with Enroute Capacities. *Operations Research*. 1998; 46(3): 406–422. Available at: DOI:10.1287/opre.46.3.406
106. Bertsimas D., Lulli G., Odoni A. An Integer Optimization Approach to Large-Scale Air Traffic Flow Management. *Operations Research*. 2011; 59(1): 211–227. Available at: DOI:10.1287/opre.1100.0899
107. Terrab M., Odoni AR. Strategic Flow Management for Air Traffic Control. *Operations Research*. 1993; 41(1): 138–152. Available at:
DOI:10.1287/opre.41.1.138
108. Richetta O., Odoni A. Solving optimally the static ground-holding policy problem in air traffic control. *Transportation Science*. 1993; 27(3): 228–238. Available at: DOI:10.1287/trsc.27.3.228
109. Navazio L., Romanin-Jacur G. The Multiple Connections Multi-Airport Ground Holding Problem: Models and Algorithms. *Transportation Science*. August 1998; 32(3): 268–276. Available at: DOI:10.1287/trsc.32.3.268
110. Andreatta G., Brunetta L. Multiairport Ground Holding Problem: A Computational Evaluation of Exact Algorithms. *Operations Research*. 1998; 46(1): 57–64. Available at: DOI:10.1287/opre.46.1.57
111. Bertsimas D., Patterson SS. The Air Traffic Flow Management Problem with Enroute Capacities. *Operations Research*. June 1998; 46(3): 406–422. Available at: DOI:10.1287/opre.46.3.406
112. Terrab M., Paulose S. Dynamic strategic and tactical air traffic flow control. *IEEE International Conference on Systems, Man, and Cybernetics*. Chicago, IL, USA, 18-21 Oct 1992, Chicago: IEEE; 1992. pp. 243–248. Available at: DOI:10.1109/ICSMC.1992.271769

113. Jayakrishnan R., Tsai WK., Chen A. A dynamic traffic assignment model with traffic-flow relationships. *Transportation Research Part C*. 1995; 3(1): 51–72. Available at: DOI:10.1016/0968-090X(94)00015-W
114. Helme MP. Reducing air traffic delay in a space-time network. *IEEE International Conference on Systems, Man and Cybernetics*. Chicago, IL, USA, 18-21 Oct 1992, Chicago: IEEE; 1992. pp. 236–242. Available at: DOI:10.1109/ICSMC.1992.271770
115. Bertsimas D., Odoni A. A Critical Survey of Optimization Models for Tactical and Strategic Aspects of Air Traffic Flow Management. 1997. Available at: <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19980004146.pdf> (Accessed: 1 October 2017)
116. Tasic V., Babic O., Cangalovic M., Hohlacov D. A model to solve en route air traffic flow management problem: a temporal and spatial case. 1st USA/Europe ATM R&D Seminar. Saclay, France, 17 - 19 June 1997, Saclay: ATM Seminar; 1997. pp. 1–8.
117. Churchill A., Lovell D., Ball M. Evaluating a new formulation for large-scale traffic flow management. *Proceedings of the 8th USA/Europe Air Traffic Seminar*. California, USA, 2 July 2009, Napa, California: ATM Seminar; 2009.
118. Sridhar B., Grabbe SR., Mukherjee A. Modeling and Optimization in Traffic Flow Management. *Proceedings of the IEEE*. 2008; 96(12): 2060–2080. Available at: DOI:10.1109/JPROC.2008.2006141
119. Sun D., Bayen AM. Multicommodity Eulerian-Lagrangian Large-Capacity Cell Transmission Model for En Route Traffic. *Journal of Guidance, Control and Dynamics*. 2008; 31(3): 616–628. Available at: DOI:10.2514/1.31717
120. Vela A., Solak S., Singhose W., Clarke JP. A mixed integer program for flight-level assignment and speed control for conflict resolution. *Proceedings of the IEEE Conference on Decision and Control*. Shanghai, China, 16-18 December 2009, Shanghai: IEEE; 2009. pp. 5219–5226. Available at: DOI:10.1109/CDC.2009.5400520
121. García Gonzalez E., Saez Nieto F., Izquierdo I. Identification and Analysis of Proximate Events in High Density Enroute Airspaces,. 7th USA/Europe ATM

- R&D Seminar. Barcelona, Spain, 02-05 July 2007, Barcelona: ATM Seminar; 2007. pp. 1–10.
122. ICAO. ATC Guidance Manual for RVSM Training in CAR/SAM Regions. 1st edn. Montréal, Canada: ICAO; 2017.
 123. Sáez Nieto FJ., Arnaldo Valdés R., García González EJ., McAuley G., Izquierdo MI. Development of a three-dimensional collision risk model tool to assess safety in high density en-route airspaces. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*. 2010; 224(10): 1119–1129. Available at: DOI:10.1243/09544100JAERO704
 124. Fulton NL., Huynh UHN. Optimisation of proximity measures for aircraft with uniform 3D straight motion. *The 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation*. Cairns, Australia, 13–17 July 2009, Cairns: Modelling and Simulation Society of Australia and New Zealand and IMACS; 2009. pp. 390–396.
 125. Sunil E., Ellerbroek J., Hoekstra J., Maas J. Modeling Airspace Stability and Capacity for Decentralized Separation. *12th USA/Europe Air Traffic Management Research and Development Seminar*. Colorado, USA, 5-9 June 2017, Denver, CO: ATM Seminar; 2017. pp. 4–12.
 126. Bayen A., Grieder P., Meyer G., Tomlin CJ. Lagrangian Delay Predictive Model for Sector-Based Air Traffic Flow. *Journal of Guidance, Control and Dynamics*. 2005; 28(5): 1015–1026. Available at: DOI:10.2514/1.15242
 127. Sun D., Bayen AM. Multicommodity Eulerian-Lagrangian Large-Capacity Cell Transmission Model for En Route Traffic. *Journal of Guidance, Control, and Dynamics*. 2008; 31(3): 616–628. Available at: DOI:10.2514/1.31717
 128. Cao Y., Sun D. A Parallel Computing Framework for Air Traffic Flow Management. *American Control Conference*. San Francisco, CA, USA, 01 July 2011, San Francisco: ACC; 2011. pp. 2771–2776.
 129. SESAR Joint Undertaking. SESAR 2020 Multi-annual Work Programme. 2015. Available at:
http://ec.europa.eu/research/participants/data/ref/h2020/other/wp/jtis/h2020-wp-multi-annual-sesar-ju_en.pdf (Accessed: 6 July 2018)

130. Drogoul F., Averty P., Weber R. ERASMUS Strategic Deconfliction to Benefit SESAR. USA/Europe Air Traffic Management Research and Development Seminar. California, USA, 2 July 2009, Napa, California: ATM Seminar; 2009.
131. Rey D., Rapine C., Fondacci R., El Faouzi N-E. Subliminal Speed Control in Air Traffic Management: Optimization and Simulation. *Transportation Science*. 2016; 50(1): 240–262. Available at: DOI:10.1287/trsc.2015.0602
132. EUROCONTROL. DDR2 Quick Reference Guide. EUROCONTROL. Available at:
[https://www.eurocontrol.int/sites/default/files/content/documents/nm/airspace/DDR2_Quick Reference Guide_ 20141205.pdf](https://www.eurocontrol.int/sites/default/files/content/documents/nm/airspace/DDR2_Quick%20Reference%20Guide_20141205.pdf) (Accessed: 15 May 2017)
133. EUROCONTROL. Statistics and forecasts (STATFOR). 2018. Available at:
<http://www.eurocontrol.int/statfor> (Accessed: 15 March 2018)
134. EUACA. The European Union Airport Coordinators Association-Who we are. 2018. Available at: <http://www.euaca.org/> (Accessed: 18 June 2018)
135. EUROCONTROL NMOC. Network Strategic Tool (NEST) User Guide. 2013. Available at: <https://www.eurocontrol.int/publications/research-network-strategic-tool-r-nest-factsheet> (Accessed: 12 January 2018)
136. Day V. The ATC Interactive Radar Simulator Operations Handbook. 2002. Available at: <http://hr.uksatse.ua/doc/opsman2k.pdf> (Accessed: 3 March 2016)
137. Sillard, L.; Vergne, F.; Desart B. Base of Aircraft Data (BADA) User Manual. 3rd edn. EUROCONTROL. Brussels: EUROCONTROL; 2000. Available at: DOI:10.1177/1090820X10391211
138. Poles D., Nuic A., Mouillet V. Advanced aircraft performance modeling for ATM: Analysis of BADA model capabilities. *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*. Florida, USA, 23-29 October 2009, Orlando, Florida.: IEEE; 2010. Available at: DOI:10.1109/DASC.2010.5655518
139. Gallo E., Navarro FA., Nuic A., Iagaru M. Advanced aircraft performance modeling for ATM: BADA 4.0 results. *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*. Oregon, USA, 15-18 October 2006, Portland, Oregon: IEEE; 2006. Available at: DOI:10.1109/DASC.2006.313660
140. Lopez Leones J. Definition of an aircraft intent description language for air

- traffic management applications. PhD. PQDT - UK & Ireland. University of Glasgow; 2008.
141. ICAO. International Civil Aviation Organization Manual on Air Traffic Forecasting. 3rd edn. Doc 8991 - Manual on Air Traffic Forecasting. Quebec, Canada: International Civil Aviation Organization; 2006. 97 p. Available at: DOI:DOC 8991 AT172213
 142. Economic Analysis policy Transport Canada. Transport Canada Assumptions Report. 2008. Available at:
http://s3.amazonaws.com/zanran_storage/www.tc.gc.ca/ContentPages/68110121.pdf (Accessed: 19 June 2018)
 143. UK Department of Transportation. UK Aviation Forecasts. 2013. Available at:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/674749/uk-aviation-forecasts-2017.pdf (Accessed: 21 February 2018)
 144. González-Arribas D., Soler M., Sanjurjo-Rivo M. Robust Aircraft Trajectory Planning Under Wind Uncertainty Using Optimal Control. *Journal of Guidance, Control, and Dynamics*. March 2018; 41(3): 673–688. Available at: DOI:10.2514/1.G002928
 145. Delahaye D., Puechmorel S., Hansman J., Histon J. Air Traffic Complexity Map based on Non Linear Dynamical Systems. *Air Traffic Control Quarterly*. October 2004; 12(4): 367–388. Available at: DOI:10.2514/atcq.12.4.367
 146. Delahaye D., Puechmorel S. Air traffic complexity based on dynamical systems. *Proceedings of the IEEE Conference on Decision and Control*. Georgia, USA, 15-17 December 2010, Atlanta: IEEE; 2010. pp. 2069–2074. Available at: DOI:10.1109/CDC.2010.5718004
 147. Prandini M., Piroddi L., Puechmorel S., Brazdilova SL. Toward Air Traffic Complexity Assessment in New Generation Air Traffic Management Systems. *IEEE Transactions on Intelligent Transportation Systems*. September 2011; 12(3): 809–818. Available at: DOI:10.1109/TITS.2011.2113175
 148. Gatsinzi D., Saez Nieto FJ., Madani I. Development of a new method for ATFCM based on trajectory-based operations. *Proceedings of the Institution of*

- Mechanical Engineers, Part G: Journal of Aerospace Engineering. 3 September 2017; 0(0). Available at: DOI:10.1177/0954410017728968
149. SESAR Joint Undertaking. PARAKE Project. SESAR. 2018. Available at: <http://www.partake-aero.eu/project/> (Accessed: 15 June 2018)
 150. Performance Review Commision. Performance Review Report: An Assessment of Air Traffic Management in Europe during the Calendar Year 2014. 2015. Available at: <https://www.eurocontrol.int/sites/default/files/publication/files/prr-2014.PDF> (Accessed: 29 July 2018)
 151. EUROCONTROL. User Driven Prioritization Process. 2017. Available at: <https://www.eurocontrol.int/udpp> (Accessed: 14 June 2018)
 152. Mutuel LH., Neri P., Paricaud E. Initial 4D Trajectory Management Concept Evaluation. 10th USA/Europe Air Traffic Management Research and Development Seminar. Chicago, IL, USA, 10-13 June 2013, Chicago: ATM Seminar; 2013.

APPENDICES

APPENDIX A - Derivation of Minimum Required Safe Time Separation (τ) from the Conventional 5 NM Separation Minimum

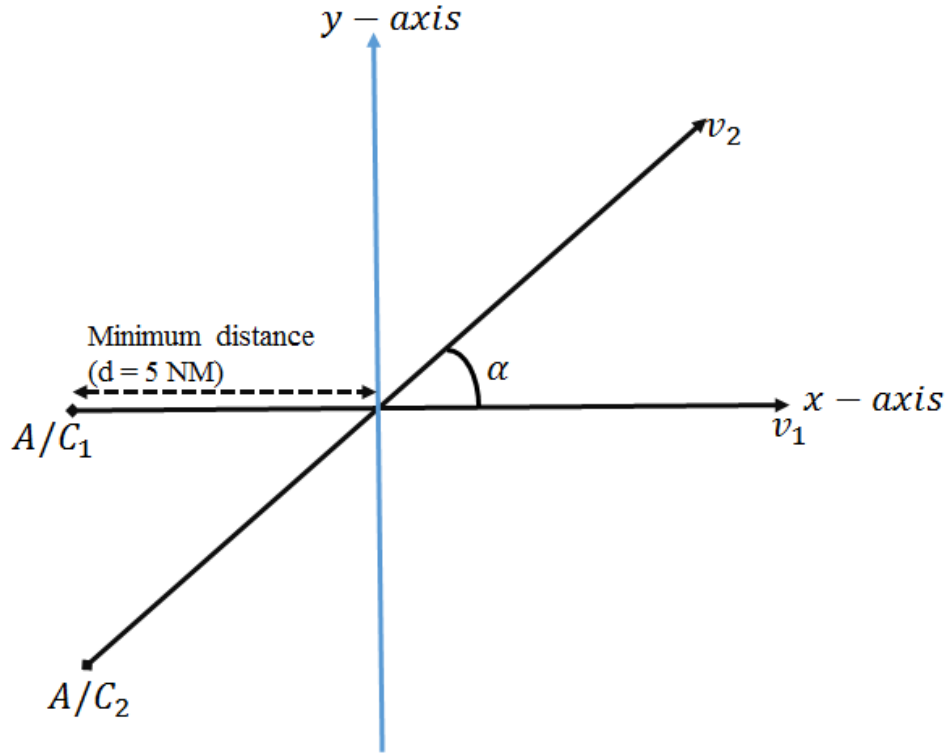


Figure 80: Geometry of conflict for deriving τ from the conventional en-route 5 NM horizontal separation minimum

From **Figure 80**, let v_1 and v_2 be the flight speeds (assumed constant) for A/C_1 and A/C_2 respectively. A/C_1 is assumed the first to arrive at junction at time t and its trajectory is considered as coincident with the x-axis. The angle α is the crossing angle between the aircraft trajectories which is also assumed constant. To translate the conventional minimum safe separation distance ($d = 5 \text{ NM}$) into the minimum safe time separation τ at junction, the following formulation is derived:

$$v_{2x} = v_2 \cos \alpha$$

$$v_{2y} = v_2 \sin \alpha$$

Let:

$$r_x = \frac{v_{2x}}{v_1}$$

$$r_y = \frac{v_{2y}}{v_1}$$

The kinematics of A/C_1 and A/C_2 are given by:

$$x_1 = v_1 t, y_1 = 0$$

$$x_2 = v_{2x}(t - \tau), y_2 = v_{2y}(t - \tau) \quad (\text{I-1})$$

Equation (I-2) can be written from Equation (I-1):

$$(x_2 - x_1) = v_{2x}(t - \tau) - v_1 t$$

$$(y_2 - y_1) = v_{2y}(t - \tau) \quad (\text{I-2})$$

From Equation (I-2), the separation distance interval between the aircraft at junction can be given by:

$$d^2 = (v_{2x}(t - \tau) - v_1 t)^2 + v_{2y}^2(t - \tau)^2 \quad (\text{I-3})$$

Then substituting for r_x and r_y we get:

$$\frac{d^2}{v_1^2} = (r_x(t - \tau) - t)^2 + r_y^2(t - \tau)^2 \quad (\text{I-4})$$

The time separation τ at junction will be minimal when the derivative of Equation (I-4) is equal to zero:

$$\frac{\partial}{\partial t} \left(\frac{d^2}{v_1^2} \right) = 2(r_x(t - \tau) - t)(r_x - 1) + 2r_y^2(t - \tau)$$

$$= (r_x(t - \tau) - t)(r_x - 1) + r_y^2(t - \tau)$$

$$= r_x t(r_x - 1) - r_x \tau(r_x - 1) - t(r_x - 1) + r_y^2 t - r_y^2 \tau$$

$$= t[r_x(r_x - 1) - (r_x - 1) + r_y^2] - \tau[r_x(r_x - 1) - r_y^2] = 0 \quad (\text{I-5})$$

Solving for t in Equation (I-5):

$$\begin{aligned} t &= \frac{r_x(r_x - 1) - r_y^2}{r_x(r_x - 1) - (r_x - 1) + r_y^2} \tau = \frac{r_x(r_x - 1) + r_y^2}{(r_x - 1)(r_x - 1) + r_y^2} \tau \\ &= \frac{r_x(r_x - 1) + r_y^2}{(r_x - 1)^2 + r_y^2} \tau \end{aligned} \quad (\text{I-6})$$

By substituting the value of t in Equation (I-4) we get:

$$\begin{aligned} \frac{d^2}{v_1^2} &= [r_x \left(\frac{r_x(r_x - 1) - r_y^2}{(r_x - 1)^2 + r_y^2} \tau - \tau \right) - \frac{r_x(r_x - 1) - r_y^2}{(r_x - 1)^2 + r_y^2} \tau]^2 \\ &\quad + r_y^2 \left(\frac{r_x(r_x - 1) - r_y^2}{(r_x - 1)^2 + r_y^2} \tau - \tau \right)^2 \end{aligned} \quad (\text{I-7})$$

Factoring out τ gives:

$$\begin{aligned} \frac{d^2}{\tau^2 v_1^2} &= [r_x \left(\frac{r_x(r_x - 1) + r_y^2}{(r_x - 1)^2 + r_y^2} - \frac{(r_x - 1)^2 + r_y^2}{(r_x - 1)^2 + r_y^2} \right) - \frac{r_x(r_x - 1) + r_y^2}{(r_x - 1)^2 + r_y^2}]^2 \\ &\quad + r_y^2 \left(\frac{r_x(r_x - 1) + r_y^2}{(r_x - 1)^2 + r_y^2} - \frac{(r_x - 1)^2 + r_y^2}{(r_x - 1)^2 + r_y^2} \right)^2 \\ &= r_x^2 + r_y^2 \frac{[r_x(r_x - 1) - (r_x - 1)^2]^2}{(r_x - 1) + r_y^2} \\ &= r_x^2 + r_y^2 \frac{(r_x - 1)(r_x - 1)}{(r_x - 1) + r_y^2} = r_x^2 + r_y^2 \frac{(r_x^2 + 2r_x + 1)}{(r_x - 1) + r_y^2} \end{aligned} \quad (\text{I-8})$$

Solving for τ in Equation (I-7) we get:

$$\tau = \sqrt{\frac{d^2}{v_1^2 (r_x^2 + r_y^2 \frac{(r_x^2 + 2r_x + 1)}{(r_x - 1) + r_y^2})}} \quad (\text{I-9})$$

APPENDIX B - Definition of Actual ECAC Area and Airspace Volume

The ECAC Area:

This ECAC area is based on the following European Civil Aviation Conference (ECAC) member states: Albania, Armenia, Austria, Azerbaijan, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Moldavia, Monaco, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, The former Yugoslav Republic of Macedonia, Turkey, Ukraine, United Kingdom.

The ECAC Airspace Volume:

The following is a definition of the actual airspace volume used for the ECAC area. This volume is defined using air-blocks and sector file formats. Coordinates are consecutively arranged as follows: Top 1st Colum to bottom - Top 2nd Colum to bottom.... Top 5th Colum to bottom.

230 3005.507 492.131 0.000 0.000 600.000 0.000 0.000 0.000 0.000 0.000

342 2610599014 0 ECAC

3660.7362 -0.8520	3153.4928 1400.8021	2678.8616 2272.0720	2198.0300 2243.3794	1659.0848 -791.4033
3779.4735 -3.6297	3138.2331 1389.6561	2663.7834 2288.9902	2210.6951 2198.6435	1659.9637 -749.6430
3780.1089 241.6280	3123.3205 1420.4857	2658.2215 2315.8169	2172.3309 2194.8198	1661.4041 -709.4685
3998.4416 500.0388	3097.3310 1415.8264	2652.6837 2332.1599	2148.8919 2169.2794	1661.2475 -669.6422
4202.2292 899.6763	3100.6361 1456.9548	2605.0642 2399.8324	2156.1224 2154.8430	1660.2033 -629.6869

4280.2590 1507.7535	3115.4676 1463.9977	2615.6588 2407.2363	2135.7003 2131.6300	1660.1292 -589.3566
4280.7369 1678.3354	3118.0738 1511.1197	2595.9198 2514.1060	2095.4745 2135.4816	1660.7713 -523.2517
4262.6361 1793.0387	3113.0054 1570.8976	2574.2311 2613.0249	1996.6732 2094.2067	1560.0106 -520.5596
4222.9455 1894.7034	3105.0188 1626.7540	2552.7040 2632.6936	1971.1873 2073.2446	1560.0325 -559.5882
4183.2744 1850.6430	3094.3866 1658.5124	2564.2764 2700.9851	1951.5158 2051.9952	1560.9158 -599.0700
4146.3936 1753.6803	3097.9112 1699.7718	2548.2897 2746.4071	1925.2343 2037.8696	1561.1341 -640.4861
4132.8848 1700.2899	3085.8163 1723.8567	2532.4170 2737.7600	2009.7504 1796.7831	1559.9172 -678.2928
4130.4599 1724.9108	3097.9265 1749.5482	2514.0442 2787.5090	2040.8089 1627.2045	1559.8806 -717.7811
4094.7323 1721.7391	3084.8760 1764.5729	2511.5979 2805.8101	2037.9599 1588.0302	1408.7795 -720.2780
4059.8673 1801.3617	3088.1175 1806.8262	2494.6442 2820.9818	2039.9185 1550.6329	1379.1596 -783.3648
4015.9549 1747.2471	3079.0940 1836.4919	2479.0337 2836.1624	2039.7654 1509.2922	1280.5969 -779.0845
3941.1218 1796.3583	3105.8902 1837.0858	2478.4492 2873.6288	2038.3021 1472.5790	1280.0932 -819.8706
3906.1462 1790.2687	3125.0927 1855.7250	2509.6675 2916.3916	2060.4372 1410.8059	1280.5160 -857.8374
3849.2639 1832.0760	3127.2972 1900.1701	2513.5002 2936.1319	2059.6641 688.8611	1279.6147 -899.9434
3824.6054 1805.8718	3126.3948 1938.4798	2475.6797 3016.1620	2189.5738 690.4598	1280.3646 -938.8212
3778.7525 1894.0304	3139.2654 1941.2526	2405.5342 3044.7200	2249.6038 689.4901	1279.7889 -979.3045
3744.1291 1871.6804	3139.2194 2029.9360	2291.7046 3023.7753	2317.3509 529.5420	1247.0201 -1024.4851
3614.2038 1646.8814	3108.0614 2070.0059	2305.9555 2932.3313	2340.6608 479.6515	1139.9082 -1140.8049
3592.0739 1562.0209	3078.4732 2057.6977	2331.8580 2883.6011	2339.4155 277.9768	1282.1320 -1321.7418
3566.6608 1690.4700	3062.3399 2121.7413	2347.5569 2893.3097	2299.5888 224.3095	1441.1788 -1500.4478
3525.6956 1645.7071	3024.3246 2139.1526	2382.2731 2882.7671	2173.6798 -93.3286	1799.7354 -1501.0912

3476.4078 1672.0074	3025.6228 2165.6401	2331.2485 2791.1988	2149.8301 -126.5822	1799.2446 -1379.5771
3452.4283 1643.6935	3014.0477 2197.7076	2330.6779 2767.8989	2150.7733 -170.6256	1800.3435 -1220.2955
3376.5767 1693.9644	3026.7670 2246.7306	2338.6474 2725.5950	2149.0287 -211.0627	1903.2947 -1044.5543
3369.4985 1689.9720	3002.9388 2295.0298	2383.4567 2686.3728	2150.6195 -250.8987	1915.8375 -1069.2316
3354.6805 1655.8207	2976.0615 2406.8292	2384.6008 2675.7673	2150.2858 -289.4008	1945.1966 -1091.7750
3347.3300 1656.4357	2957.3251 2412.6161	2364.1658 2662.2066	2149.4472 -330.0582	1972.7142 -1100.9812
3350.2941 1626.7389	2914.7460 2391.3499	2363.6544 2643.4441	2149.1927 -370.8534	2014.3611 -1094.9070
3339.0089 1595.1648	2897.3325 2398.0872	2299.3287 2663.5675	2150.5313 -410.8983	2041.6102 -1077.7221
3320.8520 1589.5147	2871.1024 2383.6855	2272.5824 2655.5481	2157.1097 -443.2203	2190.6747 -900.7266
3317.3824 1610.4181	2872.5926 2333.9334	2263.3484 2676.1088	2158.5370 -479.0514	2520.6546 -898.9598
3308.5062 1598.6195	2859.7740 2321.6803	2223.8326 2687.2924	2158.7924 -521.3770	2579.7579 -774.7116
3293.4456 1548.8420	2853.7136 2298.2916	2216.2934 2662.9471	2157.4870 -560.0672	2700.9501 -783.0498
3250.5358 1543.3100	2823.9109 2290.5264	2234.4769 2644.4981	2157.4832 -600.2284	2697.5826 -495.7588
3248.3795 1534.3658	2794.2206 2247.8950	2242.7391 2570.2731	2157.8812 -641.6821	2910.2176 -482.1512
3257.1454 1527.9229	2714.0129 2194.0389	2226.6309 2542.0929	2157.4866 -680.7680	3055.8775 -483.8906
3247.1738 1493.3971	2704.9689 2200.8141	2237.4293 2534.1892	2158.3552 -721.3949	3058.1578 -882.9065
3234.1258 1464.8172	2704.1081 2216.5234	2226.4724 2497.5344	1934.6113 -877.4312	3239.8354 -904.4120
3234.7202 1412.8505	2698.4520 2230.1622	2228.9250 2449.8847	1908.0444 -903.1726	3273.9037 -597.8196
3188.0417 1433.7251	2683.8792 2241.9127	2199.3107 2353.1922	1891.2461 -932.7965	3651.9892 -605.8146
3161.0091 1425.8427	2677.1494 2258.5782	2213.7393 2294.8225	1799.5572 -750.4617	3660.7362 -0.8520

APPENDIX C - Description of Trajectory Data File and Trajectory Examples

Table III. 1- Description of the Trajectory Data File

Extension:	SO6			
Origin	DDR2 or NEST			
Separation	Blank			
Sort	By flight segment sequence from origin to destination			
Comments	<ul style="list-style-type: none"> Describes flight trajectories, 4D-segment per 4D-segment. The trajectory comes from the NM via DDR2 or NEST The trajectory described here is an M1=Model 1=last filled flight plan. 			
Field #	Field	Type	Size	Comments
1	Segment identifier	Char	3 or 5	First point name-Last point name
2	Origin of Flight	Char	4	ICAO code
3	Destination of flight	Char	4	ICAO code
4	aircraft type	Char	4	N/A
5	Time begin segment	Num	6	HHMMSS padded with 0's
6	Time end segment	Num	6	HHMMSS padded with 0's
7	FL begin segment	Num	1 to 3	N/A
8	FL end segment	Num	1 to 3	N/A
9	Status	Char	1	0=climb, 1=descent, 2=cruise
10	Callsign	Char	7	N/A
11	Date begin segment	Num	6	Y YMMDD padded with 0's
12	Date end segment	Num	6	Y YMMDD padded with 0's
13	Flight identifier	Num	9	must be unique per flight
14	segment length	Float	N/A	in nautical miles

Table III. 2- Example Trajectory Data for Flight 1 (Flight from EGSS to LIRP)

This flight has a crossing junction with Flight 2 (Flight from LPFG to LYBE) at waypoint “TRA”.

Field 1	Field 2	Field 3	Field 3	Field 5	Field 8	Field 7	Field 8	Field 9	Field 10	Field 11	Field 12	Field 13	Field 14
EGSS_!ADBN	EGSS	LIRP	B738	80000	80018	0	10	0	RYR42TX	160909	160909	200378971	0.976596
!ADBN_!ADBo	EGSS	LIRP	B738	80018	80109	10	30	0	RYR42TX	160909	160909	200378971	1.95566
!ADBo_XIGAR	EGSS	LIRP	B738	80109	80135	30	30	2	RYR42TX	160909	160909	200378971	1.456879
XIGAR_!ADBp	EGSS	LIRP	B738	80135	80154	30	40	0	RYR42TX	160909	160909	200378971	1.09004
!ADBp_*0CLN	EGSS	LIRP	B738	80154	80426	40	40	2	RYR42TX	160909	160909	200378971	10.88526
*0CLN_!ADBq	EGSS	LIRP	B738	80426	80443	40	50	0	RYR42TX	160909	160909	200378971	0.999466
!ADBq_*1CLN	EGSS	LIRP	B738	80443	80551	50	50	2	RYR42TX	160909	160909	200378971	3.987449
*1CLN_!ADBr	EGSS	LIRP	B738	80551	80612	50	60	0	RYR42TX	160909	160909	200378971	1.792977
!ADBr_*4CLN	EGSS	LIRP	B738	80612	80626	60	60	2	RYR42TX	160909	160909	200378971	1.194935
*4CLN_!ADBs	EGSS	LIRP	B738	80626	80644	60	70	0	RYR42TX	160909	160909	200378971	1.617401
!ADBs_!ADBt	EGSS	LIRP	B738	80644	80721	70	90	0	RYR42TX	160909	160909	200378971	2.698577
!ADBt_!ADBu	EGSS	LIRP	B738	80721	80841	90	130	0	RYR42TX	160909	160909	200378971	7.550244
!ADBu_CLN	EGSS	LIRP	B738	80841	80851	130	134	0	RYR42TX	160909	160909	200378971	1.081568
CLN_EVMEK	EGSS	LIRP	B738	80851	80926	134	150	0	RYR42TX	160909	160909	200378971	3.873232
EVMEK_!ArtM	EGSS	LIRP	B738	80926	81050	150	190	0	RYR42TX	160909	160909	200378971	8.52915
!ArtM_NONVA	EGSS	LIRP	B738	81050	81109	190	198	0	RYR42TX	160909	160909	200378971	2.131924
NONVA_!DIbP	EGSS	LIRP	B738	81109	81231	198	230	0	RYR42TX	160909	160909	200378971	9.006103
!DIbP_ABtUM	EGSS	LIRP	B738	81231	81302	230	241	0	RYR42TX	160909	160909	200378971	3.702461
ABtUM_!ArtN	EGSS	LIRP	B738	81302	81431	241	270	0	RYR42TX	160909	160909	200378971	10.78737
!ArtN_!ArtO	EGSS	LIRP	B738	81431	81629	270	300	0	RYR42TX	160909	160909	200378971	15.13687
!ArtO_KONAN	EGSS	LIRP	B738	81629	81700	300	310	0	RYR42TX	160909	160909	200378971	3.782499
KONAN_!BewC	EGSS	LIRP	B738	81700	81739	310	320	0	RYR42TX	160909	160909	200378971	5.471041

!BewC_KOK	EGSS	LIRP	B738	81739	82003	320	350	0	RYR42TX	160909	160909	200378971	19.17094
KOK_!CTFT	EGSS	LIRP	B738	82003	82101	350	360	0	RYR42TX	160909	160909	200378971	7.528818
!CTFT_!CTFU	EGSS	LIRP	B738	82101	82221	360	370	0	RYR42TX	160909	160909	200378971	10.22486
!CTFU_FERDI	EGSS	LIRP	B738	82221	82503	370	370	2	RYR42TX	160909	160909	200378971	21.01523
FERDI_BUPAL	EGSS	LIRP	B738	82503	82959	370	370	2	RYR42TX	160909	160909	200378971	38.28022
BUPAL_REMBA	EGSS	LIRP	B738	82959	83135	370	370	2	RYR42TX	160909	160909	200378971	12.4461
REMBA_SPI	EGSS	LIRP	B738	83135	83515	370	370	2	RYR42TX	160909	160909	200378971	28.43702
SPI_PELIX	EGSS	LIRP	B738	83515	83557	370	370	2	RYR42TX	160909	160909	200378971	5.406268
PELIX_MATUG	EGSS	LIRP	B738	83557	83900	370	370	2	RYR42TX	160909	160909	200378971	23.69039
MATUG_!ADCA	EGSS	LIRP	B738	83900	84000	370	370	2	RYR42TX	160909	160909	200378971	7.076711
!ADCA_AMASI	EGSS	LIRP	B738	84000	84543	370	370	2	RYR42TX	160909	160909	200378971	41.44864
AMASI_UBIDU	EGSS	LIRP	B738	84543	84755	370	370	2	RYR42TX	160909	160909	200378971	15.28318
UBIDU_NONKO	EGSS	LIRP	B738	84755	85127	370	370	2	RYR42TX	160909	160909	200378971	25.32738
NONKO_RIDSU	EGSS	LIRP	B738	85127	85159	370	370	2	RYR42TX	160909	160909	200378971	4.17113
RIDSU_ABUKA	EGSS	LIRP	B738	85159	85437	370	370	2	RYR42TX	160909	160909	200378971	18.69584
ABUKA_KRH	EGSS	LIRP	B738	85437	85836	370	370	2	RYR42TX	160909	160909	200378971	28.57679
KRH_EPIXU	EGSS	LIRP	B738	85836	85931	370	370	2	RYR42TX	160909	160909	200378971	6.542384
EPIXU_NATOR	EGSS	LIRP	B738	85931	90537	370	370	2	RYR42TX	160909	160909	200378971	43.93038
NATOR_TITIX	EGSS	LIRP	B738	90537	90815	370	370	2	RYR42TX	160909	160909	200378971	18.94251
TITIX_TRA	EGSS	LIRP	B738	90815	90941	370	370	2	RYR42TX	160909	160909	200378971	10.26266
TRA_RIPUS	EGSS	LIRP	B738	90941	91317	370	370	2	RYR42TX	160909	160909	200378971	25.87666
RIPUS_GERSA	EGSS	LIRP	B738	91317	91510	370	370	2	RYR42TX	160909	160909	200378971	13.31508
GERSA_SOSON	EGSS	LIRP	B738	91510	91847	370	370	2	RYR42TX	160909	160909	200378971	26.0909
SOSON_DEGAD	EGSS	LIRP	B738	91847	92013	370	370	2	RYR42TX	160909	160909	200378971	10.28186
DEGAD_ODINA	EGSS	LIRP	B738	92013	92300	370	370	2	RYR42TX	160909	160909	200378971	19.9939
ODINA_SRN	EGSS	LIRP	B738	92300	92718	370	370	2	RYR42TX	160909	160909	200378971	31.27667
SRN_!Dxgz	EGSS	LIRP	B738	92718	93208	370	370	2	RYR42TX	160909	160909	200378971	34.84631

!Dxgz_ROBAS	EGSS	LIRP	B738	93208	93252	370	349	1	RYR42TX	160909	160909	200378971	5.368758
ROBAS_!EfrH	EGSS	LIRP	B738	93252	93425	349	300	1	RYR42TX	160909	160909	200378971	11.80835
!EfrH_!EfrI	EGSS	LIRP	B738	93425	93504	300	285	1	RYR42TX	160909	160909	200378971	4.840784
!EfrI_!EfrJ	EGSS	LIRP	B738	93504	93543	285	270	1	RYR42TX	160909	160909	200378971	4.311237
!EfrJ_!EfrK	EGSS	LIRP	B738	93543	93636	270	250	1	RYR42TX	160909	160909	200378971	6.450563
!EfrK_OSBUL	EGSS	LIRP	B738	93636	93726	250	232	1	RYR42TX	160909	160909	200378971	5.384187
OSBUL_!Dpcp	EGSS	LIRP	B738	93726	93825	232	210	1	RYR42TX	160909	160909	200378971	6.496547
!Dpcp_BEROK	EGSS	LIRP	B738	93825	94345	210	100	1	RYR42TX	160909	160909	200378971	32.98247
BEROK_!CevP	EGSS	LIRP	B738	94345	94414	100	90	1	RYR42TX	160909	160909	200378971	2.771032
!CevP_OLKIS	EGSS	LIRP	B738	94414	94640	90	52	1	RYR42TX	160909	160909	200378971	11.63468
OLKIS_!DxhH	EGSS	LIRP	B738	94640	94807	52	35	1	RYR42TX	160909	160909	200378971	5.343187
!DxhH_!DCth	EGSS	LIRP	B738	94807	94900	35	25	1	RYR42TX	160909	160909	200378971	3.757708
!DCth_!DxhI	EGSS	LIRP	B738	94900	94928	25	20	1	RYR42TX	160909	160909	200378971	1.068363
!DxhI_!DCti	EGSS	LIRP	B738	94928	95035	20	10	1	RYR42TX	160909	160909	200378971	3.206543
!DCti_!DCtj	EGSS	LIRP	B738	95035	95110	10	5	1	RYR42TX	160909	160909	200378971	1.068367
!DCtj_PIS	EGSS	LIRP	B738	95110	95122	5	3	1	RYR42TX	160909	160909	200378971	0.534558
PIS_LIRP	EGSS	LIRP	B738	95122	95145	3	0	1	RYR42TX	160909	160909	200378971	0.403634

Table III. 3- Example Trajectory Data for Flight 2 (Flight from LFPG to LYBE)

Field 1	Field 2	Field 3	Field 3	Field 5	Field 8	Field 7	Field 8	Field 9	Field 10	Field 11	Field 12	Field 13	Field 14
!ACCS_!AFbe	LFPG	LYBE	A320	82831	82844	15	20	0	ASL68Q	160909	160909	200379871	1.071728
!AFbe_!ACBz	LFPG	LYBE	A320	82844	82953	20	50	0	ASL68Q	160909	160909	200379871	3.227357
!ACBz_*1PG	LFPG	LYBE	A320	82953	83026	50	67	0	ASL68Q	160909	160909	200379871	2.696675
*1PG_!AGDm	LFPG	LYBE	A320	83026	83113	67	90	0	ASL68Q	160909	160909	200379871	3.896012
!AGDm_*2PG	LFPG	LYBE	A320	83113	83141	90	103	0	ASL68Q	160909	160909	200379871	2.788382
*2PG_PIVER	LFPG	LYBE	A320	83141	83330	103	148	0	ASL68Q	160909	160909	200379871	11.32471

PIVER_!AfvT	LFPG	LYBE	A320	83330	83431	148	170	0	ASL68Q	160909	160909	200379871	6.464157
!AfvT_!AGDn	LFPG	LYBE	A320	83431	83532	170	190	0	ASL68Q	160909	160909	200379871	7.004495
!AGDn_!BbMr	LFPG	LYBE	A320	83532	83641	190	210	0	ASL68Q	160909	160909	200379871	7.542798
!BbMr_CLM	LFPG	LYBE	A320	83641	83753	210	229	0	ASL68Q	160909	160909	200379871	8.620481
CLM_!DPnI	LFPG	LYBE	A320	83753	83927	229	250	0	ASL68Q	160909	160909	200379871	11.95515
!DPnI_BEKOS	LFPG	LYBE	A320	83927	84043	250	264	0	ASL68Q	160909	160909	200379871	9.236975
BEKOS_!BbMs	LFPG	LYBE	A320	84043	84114	264	270	0	ASL68Q	160909	160909	200379871	3.717132
!BbMs_BUBLI	LFPG	LYBE	A320	84114	84349	270	303	0	ASL68Q	160909	160909	200379871	20.19716
BUBLI_!BaYX	LFPG	LYBE	A320	84349	84719	303	340	0	ASL68Q	160909	160909	200379871	26.94355
!BaYX_LUVAL	LFPG	LYBE	A320	84719	85017	340	363	0	ASL68Q	160909	160909	200379871	22.16622
LUVAL_!BxcM	LFPG	LYBE	A320	85017	85131	363	370	0	ASL68Q	160909	160909	200379871	9.299482
!BxcM_LANVI	LFPG	LYBE	A320	85131	85351	370	370	2	ASL68Q	160909	160909	200379871	16.41022
LANVI_EPL	LFPG	LYBE	A320	85351	85525	370	370	2	ASL68Q	160909	160909	200379871	10.46969
EPL_LASAT	LFPG	LYBE	A320	85525	85914	370	370	2	ASL68Q	160909	160909	200379871	26.72337
LASAT_BEGAR	LFPG	LYBE	A320	85914	90450	370	370	2	ASL68Q	160909	160909	200379871	39.08273
BEGAR LENGI	LFPG	LYBE	A320	90450	90757	370	370	2	ASL68Q	160909	160909	200379871	21.33472
LENGI_TRA	LFPG	LYBE	A320	90757	91013	370	370	2	ASL68Q	160909	160909	200379871	15.49284
TRA_ZUE	LFPG	LYBE	A320	91013	91233	370	370	2	ASL68Q	160909	160909	200379871	16.46381
ZUE_DEGES	LFPG	LYBE	A320	91233	91516	370	370	2	ASL68Q	160909	160909	200379871	18.94084
DEGES_GAMSA	LFPG	LYBE	A320	91516	91755	370	370	2	ASL68Q	160909	160909	200379871	18.27372
GAMSA_MADEB	LFPG	LYBE	A320	91755	92144	370	370	2	ASL68Q	160909	160909	200379871	26.3692
MADEB_ELMEM	LFPG	LYBE	A320	92144	92322	370	370	2	ASL68Q	160909	160909	200379871	11.70602
ELMEM_LIZUM	LFPG	LYBE	A320	92322	93032	370	370	2	ASL68Q	160909	160909	200379871	49.39057
LIZUM_GIMIX	LFPG	LYBE	A320	93032	94314	370	370	2	ASL68Q	160909	160909	200379871	87.88692
GIMIX_MAGAM	LFPG	LYBE	A320	94314	95600	370	370	2	ASL68Q	160909	160909	200379871	88.88014
MAGAM_ZAG	LFPG	LYBE	A320	95600	95945	370	370	2	ASL68Q	160909	160909	200379871	25.61067
ZAG_VBA	LFPG	LYBE	A320	95945	100458	370	370	2	ASL68Q	160909	160909	200379871	36.22514
VBA_!DRSq	LFPG	LYBE	A320	100458	100814	370	370	2	ASL68Q	160909	160909	200379871	22.83965

!DRSq_!AtUR	LFPG	LYBE	A320	100814	100951	370	320	1	ASL68Q	160909	160909	200379871	12.52529
!AtUR_!GwJK	LFPG	LYBE	A320	100951	101026	320	300	1	ASL68Q	160909	160909	200379871	4.356387
!GwJK_LAKIK	LFPG	LYBE	A320	101026	101034	300	297	1	ASL68Q	160909	160909	200379871	1.08643
LAKIK_!AtUT	LFPG	LYBE	A320	101034	101101	297	285	1	ASL68Q	160909	160909	200379871	3.766876
LIRF_!ABHj	LIRF	EDDF	A321	82500	82611	0	25	0	DLH1PF	160909	160909	200379878	2.736839
!AtUT_!BqVc	LFPG	LYBE	A320	101101	101135	285	270	1	ASL68Q	160909	160909	200379871	4.309277
!BqVc_!BgTc	LFPG	LYBE	A320	101135	101223	270	250	1	ASL68Q	160909	160909	200379871	5.386378
!BgTc_CE	LFPG	LYBE	A320	101223	101316	250	228	1	ASL68Q	160909	160909	200379871	6.464571
CE_!AtUF	LFPG	LYBE	A320	101316	101451	228	190	1	ASL68Q	160909	160909	200379871	10.80496
!AtUF_PEROT	LFPG	LYBE	A320	101451	101623	190	155	1	ASL68Q	160909	160909	200379871	9.733025
PEROT_!FCHM	LFPG	LYBE	A320	101623	101638	155	150	1	ASL68Q	160909	160909	200379871	1.580608
!FCHM_RIGMU	LFPG	LYBE	A320	101638	101912	150	150	2	ASL68Q	160909	160909	200379871	14.77562
RIGMU_TADAM	LFPG	LYBE	A320	101912	102108	150	150	2	ASL68Q	160909	160909	200379871	11.51594
TADAM_!BqVd	LFPG	LYBE	A320	102108	102404	150	150	2	ASL68Q	160909	160909	200379871	17.33354
!BqVd_!BqVe	LFPG	LYBE	A320	102404	102459	150	130	1	ASL68Q	160909	160909	200379871	5.417944
!BqVe_!BqVf	LFPG	LYBE	A320	102459	102556	130	110	1	ASL68Q	160909	160909	200379871	5.974645
!BqVf_!BqVg	LFPG	LYBE	A320	102556	102654	110	90	1	ASL68Q	160909	160909	200379871	5.424158
!BqVg_GITRA	LFPG	LYBE	A320	102654	102845	90	66	1	ASL68Q	160909	160909	200379871	8.687421
GITRA_!HKMI	LFPG	LYBE	A320	102845	103000	66	50	1	ASL68Q	160909	160909	200379871	5.655504
!HKMI_*PA4	LFPG	LYBE	A320	103000	103043	50	43	1	ASL68Q	160909	160909	200379871	2.576332
*PA4_!HKMJ	LFPG	LYBE	A320	103043	103134	43	35	1	ASL68Q	160909	160909	200379871	3.297866
!HKMJ_!CrLD	LFPG	LYBE	A320	103134	103238	35	25	1	ASL68Q	160909	160909	200379871	4.408139
!CrLD_LYBE	LFPG	LYBE	A320	103238	103508	25	0	1	ASL68Q	160909	160909	200379871	7.153093
LFPG_!ACCS	LFPG	LYBE	A320	82800	82831	0	15	0	ASL68Q	160909	160909	200379871	1.079152

APPENDIX D - Description of Conflict Data File and Examples of 48 Crossing Conflicts in Cruise Flight

Table III. 1- Description of the Conflict Data File

Extension:	conf			
Origin	NEST			
Separation	Blank			
Sort	None			
Comments	Each line (row) contains 2 conflicting flights. This file is an input for conflict Analysis			
Field #	Field	Type	Size	Comments
1	key of flight 1	Num	9	Must be unique
2	key of flight 2	Num	9	Must be unique
3	Aircraft type	Char	4	ICAO code
4	FL at conflict	Num	1 to 3	Aircraft Flight level where conflict is identified
5	Total flight distance (A/C1)	Float	N/A	For cruise only scenarios : Total distance in cruise flight
6	Total flight distance (A/C2)	Float	N/A	For cruise only scenarios : Total distance in cruise flight
7	Speed (A/C1)	Float	N/A	In nautical miles
8	Speed (A/C2)	float	N/A	In nautical miles
9	Distance to conflict point (A/C1)	float	N/A	Distance from aircraft initial point to point of conflict
10	Distance to conflict point (A/C2)	Float	N/A	Distance from aircraft initial point to point of conflict
11	Type of conflict	Num	1	0=climb, 1=descent, 2=cruise
12	1 st waypoint of segment at conflict	Char	3 or 5	Must be unique
13	2 nd waypoint of segment at conflict	Num	3 or 5	Must be unique
14	TOA interval at conflict	Float	N/A	In minutes
15	Phase of flight at conflict point	Char	6 to 8	Cruise, Parallel or Opposite

Field 1	Field 2	Field 3	Field 4	Field 5	Field 6	Field 7	Field 8	Field 9	Field 10	Field 11	Field 12	Field 13	Field 14	Field 15
200374370	200380156	A319	360	1718.03	2016.23	438.65	399.25	944.9165	1108.9265	2	LAKTO	KAROL	0.000000	Cruise
200378755	200379290	B738	320	1173.43	1346.83	442.80	441.58	645.3865	740.7565	2	VELIS	DEMAB	0.001944	Cruise
200378892	200379290	B738	320	904.28	1346.83	423.88	441.58	497.354	740.7565	2	SUNIS	MILGO	0.006111	Cruise
200378900	200379706	B748	340	613.63	2900.42	391.68	495.80	337.4965	1595.231	2	!AEbz	LIMGO	0.008889	Cruise
200378971	200379871	A320	370	755.28	843.57	408.26	398.54	415.404	463.9635	2	TITIX	TRA	0.008889	Cruise
200379006	200379989	A320	370	502.14	468.97	407.14	390.81	276.177	257.9335	2	FFM	BOMBI	0.002778	Cruise
200379088	200379178	A320	340	400.00	872.94	333.33	443.87	220	480.117	2	NIRDU	JUIST	0.007778	Cruise
200379099	200379280	A319	370	4140.53	711.4	466.98	398.92	2277.2915	391.27	2	PON	DITAL	0.016389	Cruise
200379120	200380103	B733	370	1162.89	1081.97	417.80	413.49	639.5895	595.0835	2	!HKZu	SUNEG	0.030000	Cruise
200379123	200379128	A320	320	738.28	1225.14	417.89	415.30	406.054	673.827	2	OSDOV	MADEB	0.002500	Cruise
200379153	200379289	LJ35	370	1062.82	1049.46	403.60	391.10	584.551	577.203	2	KOVIN	RESMI	0.020278	Cruise
200379158	200379787	A320	350	512.31	533.37	409.85	400.03	281.7705	293.3535	2	DIK	LIMGO	0.003333	Cruise
200379201	200380230	E170	370	641.18	622.08	409.26	410.16	352.649	342.144	2	MTG	DIVKO	0.015278	Cruise
200379205	200379326	B738	320	1718.03	1811.31	752.42	402.51	944.9165	996.2205	2	KUGOS	KARDE	0.003056	Cruise
200379210	200379831	B738	370	955.69	884.23	400.99	392.99	525.6295	486.3265	2	BEBIX	VEGOB	0.011389	Cruise
200379216	200379303	A320	320	962.24	807.33	434.09	414.02	529.232	444.0315	2	MOKOR	OLEBA	0.010000	Cruise
200379223	200379574	B763	350	568.33	3411.27	374.72	430.90	312.5815	1876.1985	2	ZANKO	ZMR	0.006944	Cruise
200379258	200379569	B738	360	4307.98	423.53	454.27	330.02	2369.389	232.9415	2	BETAX	MAMUL	0.004722	Cruise
200379261	200379280	A319	330	639.48	711.4	391.52	398.92	351.714	391.27	2	KOVIN	RESMI	0.007222	Cruise
200379290	200379919	A320	330	1346.83	1025.49	441.58	415.74	740.7565	564.0195	2	LAMSI	LALIN	0.000833	Cruise
200379296	200379773	B738	370	857.34	1159.57	425.13	426.84	471.537	637.7635	2	DOLAP	!AnSF	0.000000	Cruise
200379303	200380060	A319	330	807.33	798.18	414.02	383.13	444.0315	438.999	2	TIRAV	TERPO	0.003056	Cruise
200379305	200379907	B772	340	905.83	5624.51	427.95	473.31	498.2065	3093.4805	2	OKRIX	BRY	0.002778	Cruise
200379307	200379661	C25A	360	683.90	943.77	410.34	382.61	376.145	519.0735	2	SRN	EKPAL	0.009722	Cruise
200379322	200379831	B738	370	475.29	884.23	365.61	392.99	261.4095	486.3265	2	RESMI	PEKIM	0.011667	Cruise
200379361	200379464	B763	340	3485.70	3696.85	436.62	434.92	1917.135	2033.2675	2	BRY	CLM	0.009444	Cruise
200379373	200379517	A320	370	997.23	804.47	409.82	402.24	548.4765	442.4585	2	GARPU	OMEDA	0.002500	Cruise
200379465	200379613	B752	370	340.27	607.1	324.07	409.28	187.1485	333.905	2	DITAL	GODIX	0.000556	Cruise
200379480	200379517	A320	370	814.40	804.47	394.06	402.24	447.92	442.4585	2	NARTI	PIGOS	0.013333	Cruise
200379505	200379972	A319	360	735.81	428.89	397.74	372.95	404.6955	235.8895	2	OKRIX	BRY	0.006944	Cruise

200379526	200379945	A321	380	1367.84	521.28	402.31	411.54	752.312	286.704	2	MATUG	NONKO	0.024444	Cruise
200379652	200379816	A319	320	1099.65	969.52	442.81	409.66	604.8075	533.236	2	NVS	PDT	0.043333	Cruise
200379652	200379852	A319	380	1099.65	903.56	442.81	410.71	604.8075	496.958	2	NVS	PDT	0.025556	Cruise
200379690	200380220	A319	380	581.91	835.16	396.76	417.58	320.0505	459.338	2	AMASI	TESGA	0.055833	Cruise
200379734	200379977	A320	370	907.73	833.54	415.75	413.33	499.2515	458.447	2	MTD	NURMO	0.016667	Cruise
200379735	200379769	CRJ9	370	703.14	804.55	409.60	392.46	386.727	442.5025	2	RIDSU	ABUKA	0.001667	Cruise
200379765	200379861	FA20	370	502.24	697.83	396.51	406.50	276.232	383.8065	2	MUN	UNKEN	0.002778	Cruise
200379867	200380060	A319	330	918.90	798.18	427.40	383.13	505.395	438.999	2	VANAD	VADOM	0.038611	Cruise
200379875	200379979	B734	340	614.81	825.55	396.65	383.98	338.1455	454.0525	2	SASAL	!HmIX	0.016667	Cruise
200379897	200379948	A320	380	923.76	836.57	416.73	401.55	508.068	460.1135	2	!BTTb	!JdWZ	0.039722	Cruise
200379924	200379964	A320	370	1144.83	1243.92	434.75	428.94	629.6565	684.156	2	KEB	BOSNA	0.005556	Cruise
200379948	200380171	B735	390	836.57	1511.02	401.55	401.16	460.1135	831.061	2	BALAP	!GHEA	0.023056	Cruise
200379964	200380154	A320	360	1243.92	1076.47	428.94	427.74	684.156	592.0585	2	GILUK	BOSNA	0.005833	Cruise
200379971	200379984	A319	370	957.02	572.32	422.21	413.73	526.361	314.776	2	VEMAK	RBO	0.000833	Cruise
200379995	200380118	A320	370	1042.73	1104.6	434.47	411.65	573.5015	607.53	2	NEA	DGO	0.005833	Cruise
200380067	200380115	B738	370	795.93	882.13	415.27	404.03	437.7615	485.1715	2	TIRAV	TERPO	0.033889	Cruise
200380146	200380246	CRJ2	360	1436.67	1161.59	442.05	389.36	790.1685	638.8745	2	GESBA	NEKUL	0.004444	Cruise
200380178	200380197	A319	370	608.95	722.27	392.87	405.01	334.9225	397.2485	2	*DIK3	VADEM	0.000278	Cruise